Study of Cross-Sectional Shapes of Ideally Hard Cylinders to achieve Invisibility for Oblique Incidence

J. M. Fernández , E. Rajo-Iglesias , M. Sierra-Castañer

Abstract— **In this work, the effect of the incidence angle on struts for reducing electromagnetic blockage using ideal hard cylinders in the antenna area is analyzed. Firstly, the characterization of the invisibility of a given object in terms of an equivalent blockage width is discussed. Then, ideally hard cylinders with oblong cross sectional shapes and hard surfaces for different incidence angles are analyzed. It is shown that the variation of incidence angle in azimuth is very sensitive in terms of blockage for TM polarization. Finally, design chart of ideal struts which reduce blockage simultaneously for TE and TM cases that give some performance goals for a final realized struts are presented.**

I. Introduction

Achieving invisibility has been the subject of extensive studies in the physics and engineering communities for decades. The use of absorbing screens [1] and antireflections coatings [2] to diminish the backscattering from objects are common in several applications, for example, you can make an object invisible to a radar with good absorbers, or with a strong scattering in others directions (monostatic approach), but this is not proper invisibility. Invisibility means to reduce the field blockage caused by an object, i.e. the incident waves are unperturbed in amplitude and phase after the object to reduce the total scattered field in particular mainly the forward scattering. The electromagnetic (EM) waves should be able to pass around or through the object without being perturbed, without reflections and absorptions but with a strong transmission and the wave phase front should be keep uniform after the object. Based on this concept in antenna applications, the EM waves radiating from or being received by an antenna are obstructed by some mechanical structures causing increased sidelobes and reduced gain of antenna [3]. The reduction of electromagnetic blockage is a problem that has received much attention since many years ago. In the antenna community, this has been treated for problems such as the blockage caused by struts or masts supporting the feed in reflector antennas or printed reflectarrays. Usually in antennas, the direction of the incident wave is known, so the struts can be designed to reduce the blockage for a given direction of incidence. A good example of how to reduce the blockage caused by struts was already presented in 1996 [4]. Typically, in such applications, the cross-section of the struts is electrically small (width much smaller than the guided wavelength). The field blockage from struts can be reduced for any polarization by making use of an oblong cross section and hard surfaces.

Following the work that has been presented in [5-6] where different oblong cross sectional shapes were analyzed and compared in terms of performances over a large frequency band for blockage reduction of cylinders with ideally hard surfaces, in this paper, we present the effect of the incidence angle on ideal struts. These ideal struts have a surface consisting of parallel ideal PEC and PMC strips, so that the strut works ideally as a hard surface for dual polarization when the direction of the strips is parallel to the plane of incidence of the plane wave on the strut. We study both the case when the plane of incidence is aligned with the strip direction to determine the sensitivity of the equivalent blockage width to direction of incidence.

The aim of this study is to evaluate the influence that the variation of the incidence angle φ in azimuth has in terms of blockage of ideal hard struts for TE and TM polarizations. The paper is divided in the next sections: Section II discusses how to characterize and quantify the blockage reduction or invisibility of struts. In Section III, some of the results of the incidence angle variation on ideally hard struts are presented and finally the conclusions of this work are drawn in section IV.

II. Characterization of Invisibility

An important issue is how to characterize and quantify the invisibility of a given object. The forward scattered field is traditionally characterized in terms of an induced field ratio (IFR) [7-8]. It is even better to characterize blockage in terms of an equivalent blockage width W_{eq} that is proportional to the product of the IFR and the physical width W. The study in this work is limited to a plane wave incident on an infinitely long scatterer which is a 2D scattering problem as shown in Fig. 1.

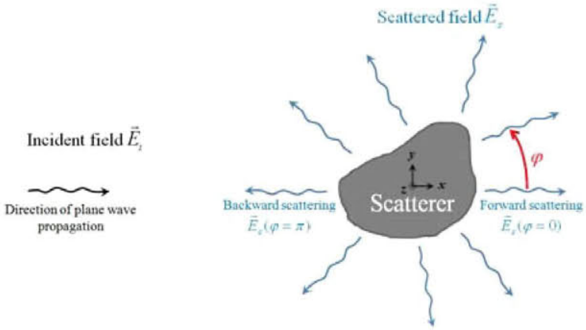

Fig. 1 Plane wave scattering (2D case).

When an infinite cylinder is immersed in an incident plane wave, its IFR is defined as the ratio of the forward-scattered field to the hypothetical field radiated in the forward direction by the plane wave in the reference aperture of width equal to the shadow of the geometrical cross section of the object (i.e. the scatterer) on the incident wavefront as:

$$IFR = -\frac{\vec{E}_s(\varphi = 0)}{\vec{E}_{ref}(\varphi = 0)} \tag{1}$$

Where E_s(φ=0) is the forward scattered electric field of the object and E_{ref}(φ=0) is the forward scattered electric field of a reference object.

The equivalent blockage width W_{eq} is by definition a complex value, where both the real part and the absolute value are representative for characterizing invisibility. Different information can be obtained from the separate analysis of its real part and absolute value. This parameter is a good measure of the blockage or shadow of a given object when it is illuminated by a plane wave. When the equivalent blockage width of the object is smaller than the physical width W, the blockage can be considered small.

$$W_{eq} = -IFR \cdot W \tag{2}$$

Where *IFR* is the induced field ratio and *W* is the physical width of the object.

For opaque objects, the blockage width becomes at high frequency equal to the physical width. The total scattered power integrated over all directions is proportional to the real part of the equivalent blockage width W_{eq} [9]. The blockage loss due to support struts in a reflector is proportional to the real part of W_{eq}, i.e. the reduction in dB of the directivity of the antennas due to the blockage. The high sidelobe level due to the struts appearing near the main lobe is proportional to the absolute value of W_{eq} as explained in [3]. From this it is evident that it is more important to reduce the real part of the equivalent blockage width than its absolute value, as the real part determines the directivity reduction and represents the scattered power averaged over all directions around the cylinder.

III. Ideally hard struts under variation of incidence angle φ

The hard surface is ideally a perfect electric conductor (PEC) for TE-case (E-field orthogonal to the cylinder axis) and a perfect magnetic conductor (PMC) for TM-case (H-field orthogonal to the cylinder axis) [10]. Also, metal struts are ideally hard for TE case. Therefore, it is the purpose of the present paper to analyze oblique incidence on PEC struts for TE-case, PMC struts for TM-case, and ideally hard PEC/PMC strip loaded struts for dual polarization.

The equivalent blockage width is readily computed by considering a plane wave incident on an infinitely long strut, which is a two dimensional scattering problem. Note that for all the results in the paper the incidence angle of the wave is varying in the azimuthal plane. The obtained results have been computed by using the FDTD software CST Microwave Studio with periodic boundary conditions as explained in [6]. This means that the strut is assumed to be infinitely long. The studied blocking objects have physical widths *W* comparable or sensibly larger than the wavelength λ_0. In the simulations we used physical cross sections of all cylinders of W=54.2 mm (f_0=8.5 GHz ⇒ λ_0=35.3 mm), and we found the equivalent blockage widths in the frequency range 0.1 to 20 GHz. Here we analyze normal incidence on ideal PMC rhombic cross section of physical width W=54.2 mm for TM-case in comparison with ideal PEC rhombic cross section for TE case for L=4W=216.8 mm. The comparison results of ideally PEC and PMC rhombic cross-section are presented as a function of the physical width W/λ_0. The ideally PMC solid rhombic cross section is modeled in CST Microwave Studio 2006 using a magnetic material with ε_r=1 and μ_r>1000 (approximation of the ideal PMC material).

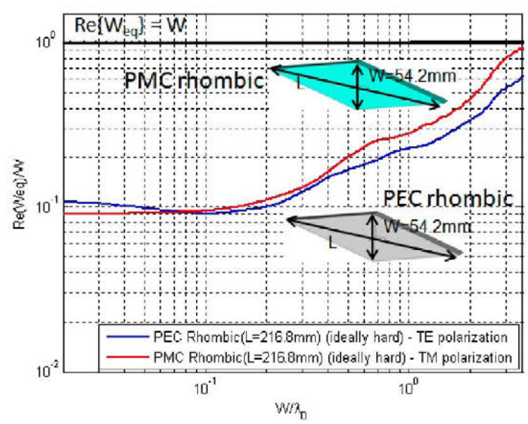

Fig. 2 Comparison of Ideally PEC and PMC rhombic cross-section under normal incidence.

We can observe in Fig. 2 that the obtained results for a ideally PMC solid rhombic cross section for TM polarization corroborate the results obtained for a PEC solid rhombic cross section for TE polarization.

Fig. 3 shows the analysis of the effect of varying the plane wave incidence angle in the azimuth plane impinged on the PEC rhombic objects for L=4W=216.8 mm in terms of equivalent blockage width.

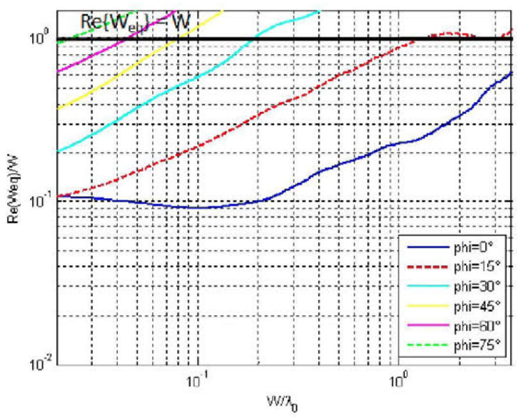

Fig. 3 Equivalent blockage width of PEC rhombus under variation of φ in the azimuth plane for TE polarization (TE case).

It is observed that the PEC rhombic cross section is very sensitive to the incidence angle φ. This means that oblong cross section is the best in terms of blockage width reduction for normal incidence (φ=0°) but worse for the variation of incidence angle φ in the azimuth plane. It is interesting to compute ideal cases of struts because it will provide more general results than studying a specific realization, which will be useful in determining fundamental physical limitations.

In Fig. 4 is depicted the effect of the variation of incidence angle φ for TM polarization in a metallic rhombus (W=54.2 mm and L=216.8 mm) with dielectric coating ε_r=2.2 and thickness $d=\lambda_0/4\sqrt{(\varepsilon_r-1)}$ =8.05 mm at 8.5 GHz. This design is narrow band. The dielectric coating is a simple way to implement TM case.

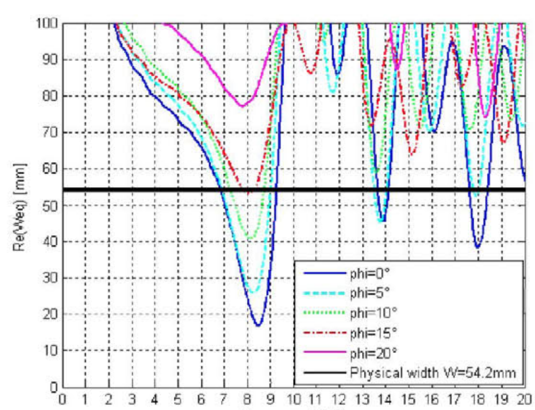

Fig. 4 TM performances for a PEC rhombus with dielectric coating ε_r=2.2 under variation of φ in the azimuth plane.

It is observed that oblong metallic rhombus with a dielectric coating is very sensitive for the TM polarization when the incidence of the plane wave is varying with φ angle. When φ>15°, the performance in terms of equivalent blockage width W_{eq} or invisibility is worse because W_{eq} > W.

Fig. 5 and Fig. 6 show TE and TM performances of a rhombic cross section with a hard surface covering realized by dielectric coating and with narrow metallic strips for dual polarization. This structure allows simultaneously blockage reduction for TE and TM polarizations.

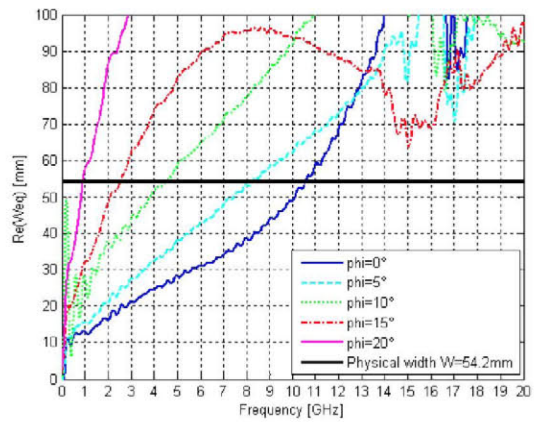

Fig. 5 TE performances under variation of φ in the azimuth plane: strip period p=6 with strip width s= 3mm.

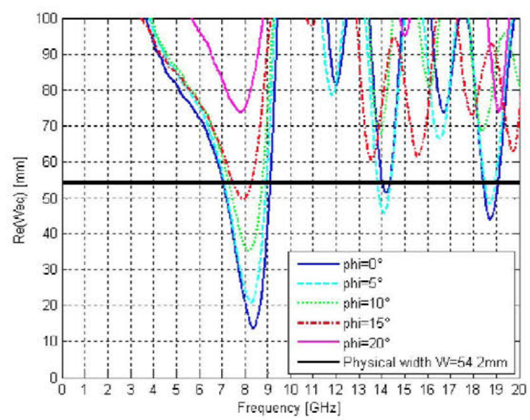

Fig. 6 TM performances under variation of φ in the azimuth plane: with strip period p=6 mm and with strip width s= 3mm.

It is observed that both TE and TM cases are very sensitive to the variation of the incidence angle φ in the azimuth plane and the blockage reduction is bad. The best case is for normal incidence (φ=0°) where the invisibility is quite good at 8.5 GHz in a narrow band for the TE and TM polarization simultaneously.

In Fig. 7, it is analysed the normal and variation of incidence angle φ in the azimuth plane on ideal PMC rhombic cross section with narrow metallic strips for dual polarization in terms of equivalent blockage width. As the rhombic cross section is a PMC material, we can observe that for TM case, the equivalent blockage width is no more narrow band as it happened with dielectric coating (Fig. 6), but it has the same behaviour as the TE case. Fig. 7 shows that for TE and TM polarization under normal incidence, this strut is almost invisible in a large frequency band.

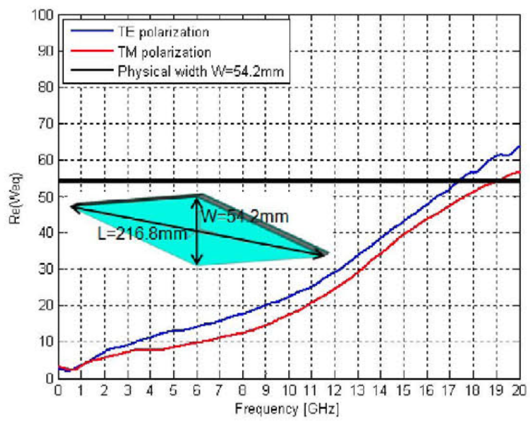

Fig. 7 Ideally PMC hard strut with narrow metallic strips (p=6mm and s=3mm) under normal incidence.

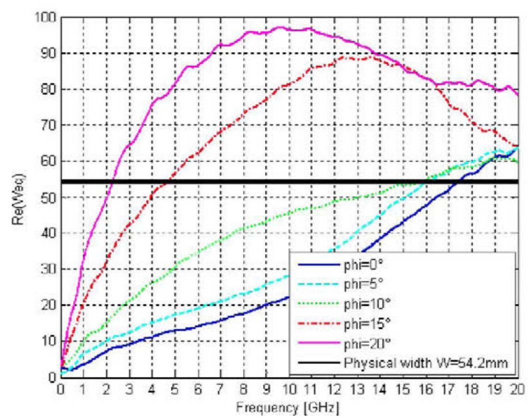

Fig. 8 Equivalent blockage width of a ideally PMC hard strut with narrow metallic strips (p=6mm and s=3mm) under variation of φ for TE case.

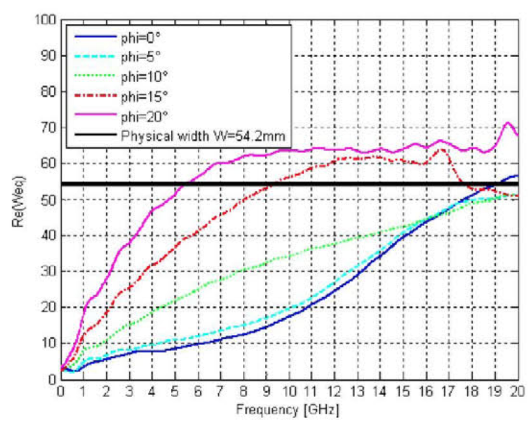

Fig. 9 Equivalent blockage width of a ideally PMC hard strut with narrow metallic strips (p=6mm and s=3mm) under variation of φ for TM case.

Fig. 8 and Fig. 9 present the effect of the incidence angle in the azimuth plane on the ideal PMC struts with narrow metallic strips. They show similar behavior and that the structure is very sensitive to the variation of incidence angle φ. At φ=20°, this structure has smaller blockage for a narrow bandwidth.

These struts have a surface consisting of parallel metallic strips on ideal PEC or PMC struts, so that the strut works ideally as a hard surface for dual polarization when the direction of the strips is parallel to the plane of incidence of the plane wave on the strut. The analysis in this paper is done in case when the plane of incidence is aligned with the strip direction. In a future work, an analysis when it deviates from it, will be realized to determine the sensitivity of the equivalent blockage width of the direction of incidence θ (oblique incidence in the elevation plane).

Fig. 10 illustrated the ideal PEC rhombic cross section strut prototype manufactured in order to contrast the previous results.

Fig. 10 Prototype: ideal PEC rhombic cross section strut of L=216.8 mm and W = 54.2 mm

IV. Conclusions

Ideally PEC and PMC hard struts have been analyzed in terms of equivalent blockage width under variation of the incidence angle φ. The performance for TE or TM case depends respectively on the realization of the PEC and PMC surfaces. As seen in the results, the performance can be seen as typical performance at the center frequency (f_0=8.5 GHz). For TM case, the bandwidth is normally narrow band and the variation of incidence angle φ in the azimuth plane is very sensitive to the blockage. While the ideal PMC solid rhombic cross section allows wider bandwidth comparable with the ideal PEC structures. The bandwidth is always limited by TM case, since TE case has wide band in most cases.

Considering ideal PMC hard rhombic cross section with narrow metallic strips, the results show wide band behavior in terms of equivalent blockage width and it is very sensitive to the variation of incidence angle φ in the azimuth plane.

It is interesting to compute ideal cases of struts because it will provide more general results than studying a specific realization, which will be useful in determining fundamental physical limitations. The obtained results of ideal struts allow getting design chart that gives some performance goals for a final realized strut. Both factors, shape and realization of the hard surface for the struts are fundamental to achieve invisibility.

ACKNOWLEDGMENT

The simulations presented in this article have been realized using CST Microwave Studio Suite 2006 under a cooperation agreement between Computer Simulation Technology (CST) and Universidad Politécnica de Madrid. This research work is been supported by a Spanish Government grant (FPU).

REFERENCES

[1] R. L. Fante and M. T. McCornack, "Reflection Properties of Salisbury Screen", *IEEE Trans. on Antennas and Propagation*, Vol. 36, N° 10, pp. 1443-1454, October 1988.

[2] J. Ward, "Towards Invisible Glass", *Vacuum*, Vol. 22, pp. 369-375, 1972.

[3] P.-S. Kildal, E. Olsen and J. A. Aas, "Losses, Sidelobes and Cross-Polarization caused by Feed-Support Struts in Reflector Antennas: Design Curves", *IEEE Trans. on Antennas and Propagation*, Vol. 36, N°2, pp. 182-190, February 1988.

[4] P.-S. Kildal, A. A. Kishk and A. Tengs, "Reduction of Forward Scattering from Cylindrical Objects using Hard Surfaces", *IEEE Trans. on Antennas and Propagation*, Vol. AP-44, Issue 11, pp. 1509-1520, November 1996.

[5] E. Rajo-Iglesias, J. M. Fernández and P.-S. Kildal, "Blockage Reduction of Rhombic Cylinders using Meta-Surfaces", *Proc. of IEEE AP-S international Symposium 2008*, San Diego, USA, pp. 1-4, July 2008.

[6] J. M. Fernández, E. Rajo-Iglesias, P.-S. Kildal, P. Jacobsson, T. Rylander and M. Sierra-Castañer, "Comparisons of Blockage Widths of Ideally Hard Cylinders of Different Cross-Sectional Shapes", *Proc. of IEEE AP-S international Symposium 2008*, San Diego, USA, pp. 1-4, July 2008.

[7] A. F. Kay, "Electrical Design of Metal Space Frame Radomes", *IEEE Trans. on Antennas and Propagation*, Vol. AP-13, pp. 188-202, March 1965.

[8] W. V. T. Rusch, J. Appel-Hansen, C. A. Klein and R. Mittra, "Forward Scattering from Square Cylinders in The Resonance Region with Application to Aperture Blockage", *IEEE Trans. on Antennas and Propagation*, Vol. AP-24, pp. 182-189, March 1976.

[9] A. Ishimaru, "Electromagnetic Wave Propagation, Radiation and Scattering", *Prentice-Hall*, 1991.

[10] A. A. Kishk and P.-S. Kildal, "Asymptotic Boundary Conditions for Strip-Loaded Scatterers Applied to Circular Dielectric Cylinders Under Oblique Incidence", *IEEE Trans. on Antennas and Propagation*, Vol. 45 N° 1, pp. 51-56, January 1997.