Introduction to Canonical Surfaces in Electromagnetic Computations: PEC, PMC, PEC/PMC Strip Grid, DB Surface

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Abstract: Perfect electric conductor (PEC) is often replacing conducting materials in electromagnetic computations, at least during initial and conceptual studies. Similarly, it is possible to replace metamaterials by their ideal counterparts. The latter are herein referred to as canonical surfaces. The use of canonical surfaces will strongly reduce computation time during initial analysis and proof of concept when searching for new metamaterial applications. The canonical surfaces are herein considered to include PEC, PMC (Perfect Magnetic Conductor), PEC/PMC strip grids representing soft and hard surfaces, and the recently introduced DB surface, which is believed to represent an ideal electromagnetic bandgap surface. The paper discusses the characteristics and limitations of these different canonical surfaces, and emphasizes the need for having them available for use in commercial electromagnetic codes.

Keywords: PEC, PMC, Soft and Hard, DB Boundary.

1. Introduction

The present paper will explain simplified and ideal boundary conditions referred to as canonical surfaces that are useful for the further development and unification of the metamaterials area. These ideal boundary conditions include perfect electric conductors (PEC), perfect magnetic conductors (PMC), ideal soft and hard surfaces [1] (represented by PEC/PMC strip grids [2]), and the newly introduced DB surface [3]. All of them have a physical realizable counterpart. The physical counterpart of the DB surface is believed to be the electromagnetic bandgap surface (EBG).

The anisotropic soft surface was introduced in analogy with acoustics to explain why certain surfaces stopped waves from propagating along them. Later, isotropic high impedance surfaces were introduced (or more correctly realized as such), and these could stop surface waves as well [4]. The latter are now more correctly referred to as electromagnetic bandgap (EBG) surfaces, because most so-called high impedance surfaces only have high surface impedance for normal incidence, whereas the wave-stop characteristics are related to the non-existence of surface waves along the surface, and not to this high surface impedance. The hard surface was introduced as the complement to the original soft surface, allowing waves of any polarization to propagate freely along it. This was then used for removing blockage by cylindrical objects [5], nowadays referred to as cloaking [6]. The guest editorial in [7] gave a joint comprehensive presentation of the EBG surfaces and the soft and hard surfaces by defining ideal canonical surfaces and their boundary conditions, but it also stated the lack of a simple boundary condition for the EBG surface. The present paper explains how the newly introduced DB surface [3] provides such a simple boundary condition and thereby can be referred to as an ideal EBG surface, or in other words an ideal, isotropic and polarization-independent soft surface. However, the boundary condition at the DB surface has an anomaly for normal incidences that causes problems for some cases and therefore needs to be repaired. This paper makes reparation that requires a TE/TM decomposition of the field.

The simplification offered by the canonical surfaces has already proven to be advantageous for simplifying numerical solutions [8] and generation of conceptually new microwave devices, such as the invisible hard struts in [5] representing the first metamaterial cloak, and the new gap waveguide described in [9]. The latter is a generalization of the single-wall hard parallel-plate waveguide [10], and represents a way to guide local waves (beams) in the gap between parallel metal plates. It originates from the miniaturized hard waveguide in [11-12], and the concept can also be used to package microstrip circuits [13].

2. Canonical Surfaces: PEC, PMC, PEC/PMC strip grid, DB Surface

Table 1. **Left:** Characteristics of different types of canonical surfaces with respect to propagation of waves along the surface for different E-field polarizations. VER means vertical polarization (i.e. TM-case), HOR means horizontal (i.e. TE-case). The background color and pattern symbolize the PEC (yellow), PMC (blue) and PEC/PMC strips (parallel yellow and blue strips). The different orientations of the colored strips for the soft and hard cases symbolize STOP (current fences) and GO (current lanes) characteristics for waves propagating from left to right (as shown by the arrows) in the paper plane. The colored background in the box of the DB surface is a PMC-type EBG symbolized by the texture of Sievenpiper's EBG mushroom surface. The D´B´ surface has no known realization. **Right:** Ideal boundary conditions of the canonical surfaces. The boundary conditions of the DB and D´B´ surfaces are in Lindell's work described in terms of the D and B fields rather than E and H, but here we have chosen the more common E and H field boundary conditions that are equivalent to the original boundary conditions for our practical case considering the interface to an air-filled region.

Canonical Surface		E-field Polarization		Ideal boundary condition (in xy-plane)
		VER (TM)	HOR (TE)	
PEC		GO	STOP	$E_x = E_y = 0 \;\&\; \partial E_z / \partial z = 0$
PMC		STOP	GO	$H_x = H_y = 0 \;\&\; \partial H_z / \partial z = 0$
PEC/PMC Strip grid	SOFT	STOP	STOP	$E_y = 0 \;\&\; H_y = 0$
	HARD	GO	GO	$E_x = 0 \;\&\; H_x = 0 \; \partial E_z / \partial z = 0$
DB surface (PMC-type EBG?)		STOP	STOP	$E_z = 0 \;\&\; H_z = 0$ (incomplete)
D´B´ surface (no realization)		GO	GO	$\partial E_z / \partial z = 0 \;\&\; \partial H_z / \partial z = 0$ (incomplete)

Artificial surfaces like soft and hard surfaces, artificial magnetic conductors, high impedance surfaces, and electromagnetic bandgap surfaces can be used to control wave propagation: enhance it in desired directions, stop it in undesired directions, and improve polarization characteristics of both. These properties can be explained by reference to Table 1. This was first presented in [2], updated and improved in [6], and it is here updated by introducing or rather proposing the DB surface as a canonical surface having similar property as the EBG surface. The table contains also the related D´B´ as explained below.

The boundary conditions of the ideal canonical surfaces are also added to Table 1, but with a notice of incompleteness for the DB surface due to the anomaly. Notice that we did not impose any polarization dependence for the boundary conditions as they are supposed to be functions of the surface type only. Also, we did not impose any frequency dependence because we consider ideal surfaces. Actual realizations of the canonical surfaces will always have strong frequency dependences (except for the PEC).

The explanations of the surfaces are:

Perfect Electric Conductor (PEC): This surface is widely used in most EM modeling and computations as it describes metal conductors very well when analyzing guiding or radiating properties. The boundary conditions are well defined.

Perfect Magnetic Conductor (PMC): The EM field theory is easily extended to allow a PMC. This surface does not exist naturally, but it can be realized artificially within frequency bands and is then referred to as an artificial magnetic conductor (AMC). The ideal boundary conditions are well defined.

PEC/PMC strip grid: This is the physical equivalent of an ideal soft/hard surface. The surface has locally infinite and unidirectional electric and magnetic conductivity, i.e. both the electric and magnetic currents can only flow in the strips direction, which could follow any arbitrarily shaped path on planar or non planar form. For the transverse soft case (STOP surface) the PEC/PMC strip grids form electric/magnetic current fences that stop wave propagation, and for the longitudinal hard case (GO surface) they form electric/magnetic current lanes that enhance wave propagation. The ideal boundary conditions are well defined, and there exist many realizations.

DB surfaces: This surface has the boundary condition that both the vertical E and vertical H field components are zero. Thereby, it stops waves at grazing angles for both horizontal and vertical polarizations for all angles of incidence. Therefore, it works similar to an EBG surface, like an isotropic soft surface. The boundary condition is well defined, except for the case of a plane wave under vertical (normal) incidence to the surface. For normal plane wave incidence the incoming fields has no vertical components, and therefore the boundary condition is automatically satisfied for any reflection coefficient. Thus, the reflection coefficients as well as the boundary conditions are undefined for normal incidence. The reflection coefficient of a realized EBG surface has always a phase that varies with elevation angle for TE case, so that it appears like a PEC for gracing incidence and like a PMC for normal incidence. The anomaly of the reflection properties of the ideal DB surface for normal incidence has therefore some relation to peculiarities of its practical counterpart. This anomaly causes some strange unphysical field solutions for some special cases and needs to be repaired, as discussed in the next section.

D´B´ surfaces: By analogy with the DB surface, the D´B´ surface is an isotropic hard surface. The tables talk for themselves. However, in contrast to the DB surface no realization of a D´B´ surface is known so it has at present no practical interest.

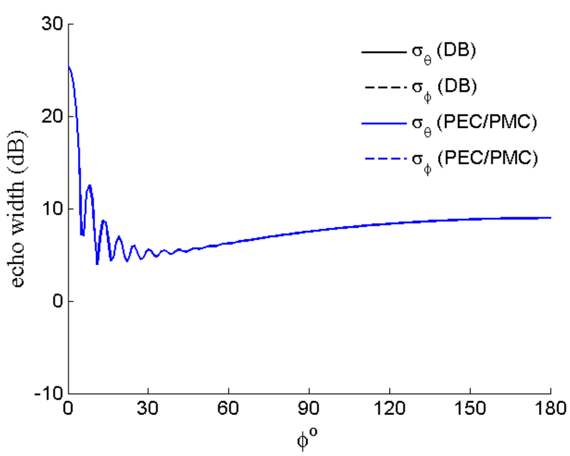
The characteristics of the three different surfaces with respect to polarization of the grazing waves are illustrated in the table. The PEC supports vertically polarized waves that can propagate with strong amplitude; it is a "GO" surface for vertical polarization. These propagating waves are not really surface waves in the mathematical sense, because they are represented by a branch point rather than a pole in the spectral domain. Thus, they are for the ideal case surface waves at cut-off (linked to the corresponding space wave) rather than normal isolated surfaces waves trapped by the surface. However, when the surface has a thin dielectric coating the wave along the surface becomes a TM (with respect to normal) surface wave (i.e. a pole). The PEC STOPs effectively horizontally polarized waves, because the horizontal field component is zero. The PMC performs naturally in the opposite (dual) way; it is a GO surface easily passing waves for horizontal polarization and a "STOP" surface for vertical polarization (see table). The classical soft/hard surfaces can be represented physically by a PEC/PMC strip grid as explained above and illustrated in the table as well. This will STOP waves propagating with both horizontal and vertical polarizations when the strips are oriented transverse to the direction of propagation (soft case), and it will allow the waves to pass (i.e. GO) when they are oriented longitudinally in the same direction as the waves propagate (hard case).

The soft/hard surfaces were originally realized by metal corrugations or metal strips loading a grounded substrate. The soft/hard characteristics appear when they are oriented transversely/longitudinally with respect to the direction of wave propagation. For the soft case, they form so-called electric and magnetic current fences that stop the waves, and for the hard case they form electric and magnetic current lanes that enhance wave propagation.

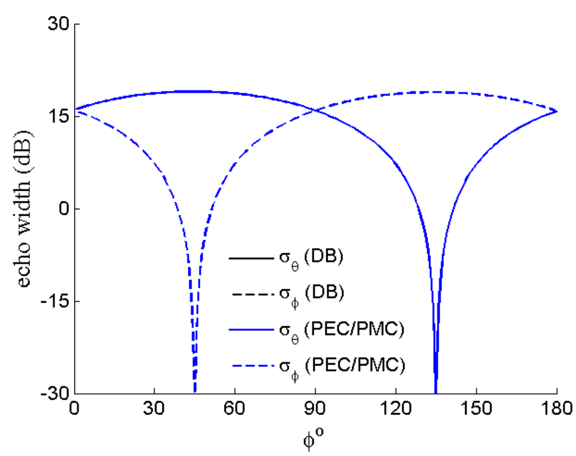
3. Investigation of the Anomaly of the DB Surface

The 2-D periodic EBG surface behaves normally like a PMC within some frequency band (or bands) and for wave incidence close to normal. However, for wave incidence close to grazing and within the lower part of the same frequency band, the EBG surface behaves more like a transverse PEC/PMC strip surface, i.e. like a soft surface stopping waves. The original anisotropic 1-D periodic soft surface has STOP characteristics over an infinite bandwidth for the TE case (i.e. horizontal polarization). Still, the 2-D EBG surface is preferable in some applications (such as in the cut-off regions of gap waveguides) because it is isotropic, stopping waves from any direction. For grazing incidence the 2-D periodic EBG surface normally transforms from STOP to PMC-type surface at the upper edge of the stop band. These rather complex characteristics of the 2-D EBG surfaces make it impossible to categorize them completely in terms of PEC and PMC boundary conditions. However, as stated in the table the DB surface characterizes them well. However, practical EBG surfaces may also be used as PMC ground planes (for low profile electric current radiators), and this characteristic the DB surface cannot capture. In fact, as already stated before, the DB boundary condition has no effect on normal incident waves, i.e. the solution is undefined, so the boundary condition is incomplete and needs to be repaired.

In order to understand the characteristics of the DB surface and confirm our assessments, we compared its behavior with other canonical surfaces. The series solutions for the scattering from circular cylinders are considered. The scattering from a DB circular cylinder due to oblique plane wave incidence is found to be exactly the same as the scattering from a circular cylinder of PEC/PMC strips directed longitudinally parallel to the cylinder axis. Another cylinder with circumferentially directed PEC/PMC strips is compared with the DB cylinder due to grazing incidence plane waves (along the cylinder axis). It should be stated that the series solution of the PEC/PMC cylinders were verified against the method of moment solutions. These two cases are shown in Fig. 1. They are obtained by TE/TM decomposition of the field, so they are not general. More results will be given in the oral presentation.



(a)



(b)

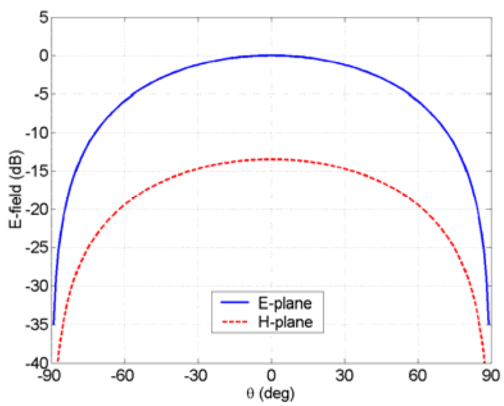
Fig. 1. Echo width of a circular cylinder with DB boundary condition with ka = 10π compared with (a) longitudinal PEC/PMC strips forming a circular cylinder due to normal plane wave incidence with polarization angle 45^o (TE and TM polarization) and (b) circumferential PEC/PMC strips forming a circular cylinder due to grazing plane wave incidence. Curves not seen explicitly coincide identically with their counterpart.

In order to find a boundary condition that will describe ideal EBG surface in general, several attempts have been made to repair the DB boundary conditions. The anomaly for normal incidence must be removed, and the surface should for incident TE waves transform from working like a PEC for gracing incidence to working like a PMC for normal incidence [14]. The following boundary conditions suitable for TE/TM decomposed waves, respectively, solve the problem:

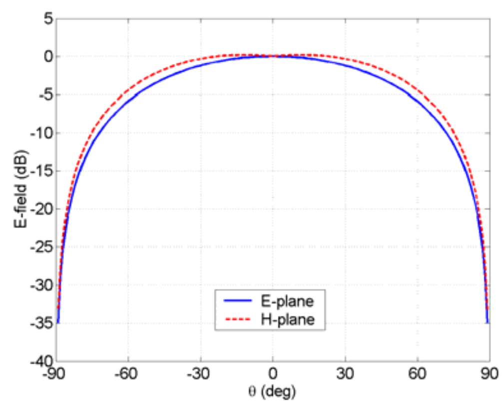
$$H_z - jH_{\tan} = 0, \qquad E_z = 0. \tag{1}$$

Applying it gives reasonable agreement between the ideal EBG structure (described with modified DB boundary conditions), and the mushroom structure (i.e. practical realization of the EBG structure). Fig. 2.a shows the comparison of the radiation patterns of a short dipole over the DB surface (the working frequency is 10 GHz; the height of the dipole is 1 mm). It can be seen that there is a big difference in the E-plane and H-plane patterns: in the E-plane we have a dipole over a PMC surface (constructive imaging), while in the H-plane we have a dipole over the PEC (destructive imaging). This is of course erroneous because the E- and H-planes coincide in the normal (vertical) direction $\theta = 0$, so at least in this direction the results must be identical. However, the repaired DB boundary conditions remove the huge difference between E- and H-planes and make them equal in the vertical direction, and, we get a radiation pattern that looks as expected from an ideal EBG surface.

However, the repair in (1) cannot be generally applied as it requires a TE/TM decomposition of the field that is not possible to do in general FDTD and FEM codes.



(a)



(b)

Fig. 2. Radiation pattern of a short dipole over the DB surface; (a) Original DB boundary conditions, (b) Repaired DB boundary conditions requiring TE/TM decomposition.

4. Conclusions

The paper has summarized previously defined canonical surfaces for use in electromagnetic computations and conceptual studies. The PEC is well accepted and used a lot, and also the PMC to some degree, at least in theoretical work and as symmetry planes in EM computations, but in most computational codes the PMC cannot be used for finite and arbitrary shape and when being curved. The authors hope that this overview can stimulate software vendors and developers to include arbitrarily shaped PMCs in their codes. This is easily done and will add important capabilities. Similarly, it would be useful if arbitrarily shaped PEC/PMC strip grids with arbitrary strip orientations could be included for general usage. The PEC/PMC strip grids represent soft and hard surfaces and can open up for more fundamental studies and principally new hardware solutions. The PEC/PMC strip grid is also easy to implement as illustrated in [8].

The DB surface has characteristics similar to an ideal EBG surface, i.e. an isotropic soft surface, but the present paper has highlighted some anomalies that needs to be resolved by more research and repaired before they can be used in general codes. For a canonical boundary condition to be useful we must require that it is simple and general. We have proposed a simple repair that seems to work, but it is limited by a required TE/TM decomposition. Unfortunately, a repaired DB boundary condition cannot be restricted to be valid only under TE/TM decomposition or as a correction in the plane wave spectral domain. It must be possible to use it in general 3-D Moment method, FDTD and FEM codes. So, more research is needed.

There has also previously been introduced a so-called D´B´ surface, but this has no known practical counterpart so it does not have so much interest at the moment. This suffers from a similar anomaly as the DB surface and needs repair.

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