Holistic Analysis of Conformal Antennas using the Cylindrical TLM Method

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***Abstract*—The impact of deformations on wearable antenna performance has been analyzed both experimentally and computationally. However, the reported results have been inconsistent and often contradictory. This paper highlights how the choice of computational mesh, namely cubic and curvilinear cylindrical mesh, that are applied to the problem of cylindrically bent antenna can affect the results and subsequent conclusions. By deploying both meshes within the same time-domain numerical algorithm means that the differences in results can only be attributable to the discretization method used. Finally, a cylindrical mesh is used to further characterize the impact of bending on antenna resonant frequency, bandwidth and radiation pattern. Bending in both E- and H- plane is considered.**

***Index Terms*—Bending effect, textile antennas, patch antennas, TLM method.**

I. Introduction

RAPID development of wearable technology requires reliable on-body wearable antennas with stable in-situ performance. Antenna deformations caused by the curvature or movement of the body on which they are mounted can produce complex shapes, making its systematic characterization, either by computer models or experiments, very difficult.

The most popular choice of wearable antenna is a patch antenna, and the case of a cylindrically bent patch antenna, as shown in Fig.1, has attracted considerable attention due to its simplicity. In particular, the case of cylindrical bending is the only deformation that can be generated using standard CAD approaches based on Boolean operators that are commonly deployed in commercial software such as Ansys and CST Simulation Studio [1-4]. Recently, a computer graphics approach has been reported for generating arbitrary antenna geometries [5]. However, this approach needs to be used carefully in the context of electromagnetic (EM) simulations as the computer graphics methods introduce unwanted distortions in the antenna geometry that need to be minimized [5].

Even though the case of cylindrical bending represents the simplest type of deformation (Fig.1(a)), it nevertheless gives an indication of how resilient an antenna is to potential deformations. For example, a patch antenna can be bent along its length (E-plane bending) or width (H-plane bending). In the available literature, the impact of such bending has been investigated using analytical models [6-9], commercial software packages [1-4,10-13], and experimental characterization [3,4,10,11,13-16]. However, these reports are not conclusive, in the sense that they often draw conflicting conclusions. For example, early analytical approaches for assessing the impact of bending on antenna performance report that the resonant frequency is not affected by curvature, rather the radiation patterns are significantly affected [6-8]. A more recent analytical model reports that when the curvature is increased, the resonant frequency increases [9] which is contradictory to conclusions of [7,8]. Numerical simulations also report an increase in resonant frequency with increased bending [1,2,12]. However, [13] reports a variable trend in resonant frequency due to bending, a distorted radiation pattern whilst the bandwidth remains largely unaffected. The available experimental results provided by [3,14,15] show that the resonant frequency of a wearable antenna remains largely

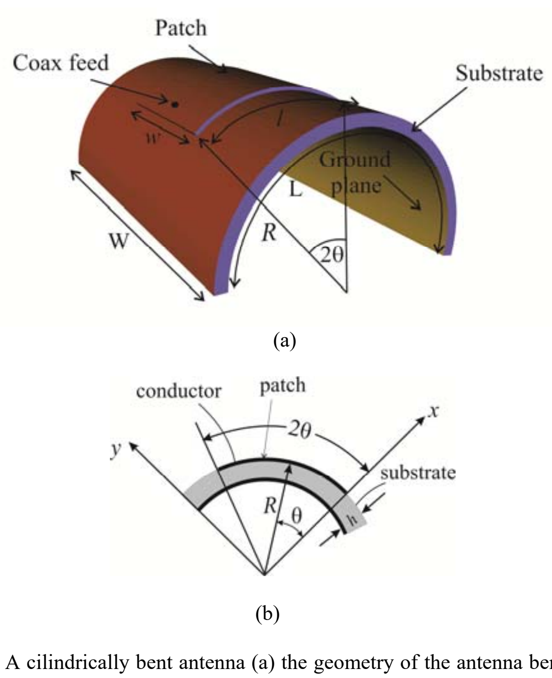

Fig.1. A cilindrically bent antenna (a) the geometry of the antenna bent in the E-plane; (b) the cross-section of the cylidnrically bent antenna.

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unaffected when the antenna is bent in the H-plane and that the resonant frequency reduces when the antenna is bent in the E-plane, whilst results of [10,11,16] report an increase in the resonant frequency with curvature. Recently, the simulated and measurement results of [4] report that the resonant frequency of a rectangular patch antenna behaves differently for bending angles smaller or larger than 40°. Majority of reports state that bending predominantly affects the resonant frequency of the antenna and that E-plane bending has a greater impact on antenna resonant frequency than H-plane bending [3,4,14-16]. According to [10,13,15,16] increasing the bending curvature in either the E- or H-plane broadens the radiation pattern of antenna. The impact of bending on antenna bandwidth has not been widely considered and the results are still inconclusive; [13,14] claim that bending does not cause severe changes to antenna bandwidth, [10,11] report the decrease in the bandwidth for both E- and H-plane banding, [15] reports the increase in bandwidths for both E- and H- plane bending and [16] reports that the change in the bandwidth is dependent on the bending angle for the H-plane bending. The reported papers have predominantly considered textile antennas for 2.4 GHz band.

As can be seen, the conclusions are not consistent. Whilst the importance of experimental measurements is acknowledged, it is also emphasized that these can be affected by a variety of issues whereas the simulations, on other hand, offer a more controlled way of analysis. However, the simulations are also not free of errors and tests need to be conducted to ensure that results have converged with respect to the parameters of the method. In case of numerical simulations, the most obvious parameters are the type of the mesh discretization deployed and its resolution as well as the size of the overall computational domain. However, the majority of published results do not state the simulation parameters used and the reader might be led to believe that the reported results are free of such errors.

The type of the mesh used in numerical simulations is an important consideration from the point of accuracy and numerical efficiency. It is well known that the cubic mesh applied to curved structures introduces numerical discretization errors. Mesh refinement techniques can largely reduce the discretization errors but do not fully eliminate them. Structure aligned meshes, on the other hand, that perfectly align to the structure would be highly advantageous in terms of discretization. For the case of cylindrically bent antenna the structure aligned mesh would be a cylindrical mesh with the unit cell as given in Fig.2(a).

The goal of this paper is twofold: (i) to demonstrate the impact of discretization on a particular study of cylindrically bent antennas, and (ii) to use cylindrical mesh to comprehensively analyse the impact of bending on the parameters of 2.4 GHz cotton-based textile antenna [4]. To meet the first goal, two different types of discretization meshes, namely Cartesian and cylindrical, implemented within the numerical Transmission Line Modelling (TLM) method [17, 18], are used to investigate how the choice of the mesh impacts the simulated antenna performance. The TLM method has been previously used to investigate the mesh impact on textile antenna modelling in [19]. However, that paper focused only on the mesh issues, both cubic and cylindrical, providing conclusions on differences in results when different meshes are applied to model antenna bent in an E-plane. Here, more comprehensive analysis related to the influence of the mesh is given, which includes more rigorous mesh convergence analysis, an impact of the padding and comparison of computational requirements. More importantly, this paper provides novel analysis of the considered antenna including the impact of a bending on antenna performance for different antenna thicknesses, namely the antenna resonant frequency, the bandwidth and the far field radiation profile for the bending in both E- and H-planes.

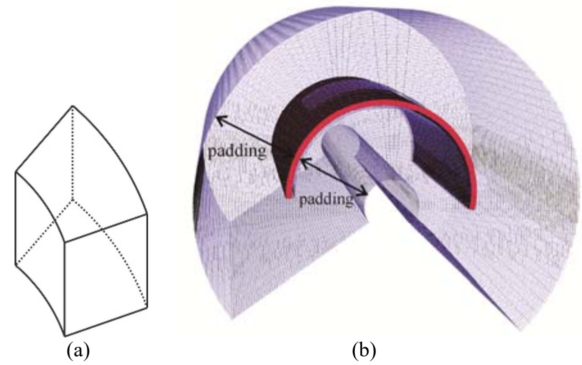


Fig.2. An antenna model in a cylindrical grid, (a) a cylindrical TLM cell, (b) the geometrical representation of the antenna bent in the E-plane inside the computational box.

The TLM method based on the Cartesian mesh is a well-established time-domain numerical method based on equivalences between Maxwell's equations and transmission line theory [17]. The method is fully characterized and validated and the reader is specifically referred to [17-25]. The TLM method based on a cylindrical mesh is a relatively recent variant and has been validated on applications of circular patch antennas and cylindrical resonant cavities [18-22]. However, in reported applications the structure analyzed was placed at the center of the cylindrical coordinate system and the computational domain was bounded by a larger cylinder that completely surrounded the problem of interest. At the center node, i.e., at the origin of the cylindrical grid, a magnetic or electric wall is imposed depending on the field solution being sought [23]. For the purposes of this paper the computational box is defined to be a section of the larger cylinder, as shown in Fig.2(b), on which matching boundary conditions are imposed, resulting in a significant reduction of the overall computational problem. The obvious down-side of the cylindrical mesh is the lack of generality as it is ideally suited only to problems that align to the cylindrical coordinate system.

This paper is structured as follows: Section II describes the computational modelling issues when a 2.45 GHz antenna is meshed using cubic and cylindrical mesh. Section III uses a cylindrical mesh to further study the impact of a bending on antenna performance, namely the antenna resonant frequency, the bandwidth and the far field radiation profile. Bending in both E- and H-planes is considered. Section IV summarizes the main conclusions of the paper.

II. Computational Modelling Issues

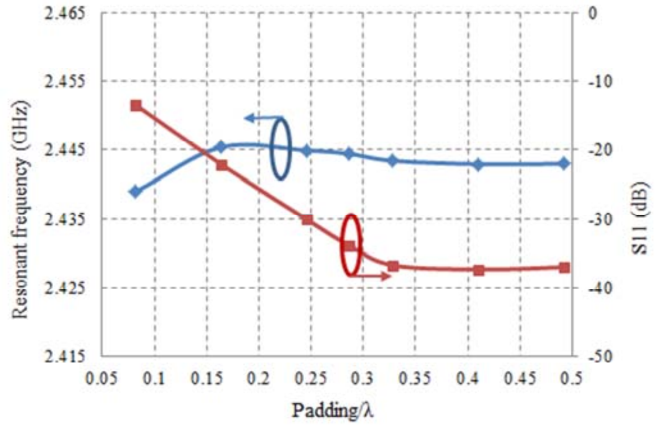
This section discusses and compares modelling issues when two different spatial discretizations are applied to the problem of cylindrically bent antennas, namely a cubic mesh, and a cylindrical mesh. The following issues are considered: the size of the computational box, the mesh size and the corresponding computational requirements.

The cotton-based textile patch antenna is considered and taken from [4]. The resonant frequency of the flat patch antenna according to the cavity model theory is 2.45 GHz. The length and the width of the radiation patch are $l = 39.5$ mm and $w = 50$ mm, respectively, while the length, L, and the width of the substrate, W, and ground plane are $W = L = 100$ mm. The antenna is realized on a substrate of relative permittivity $\varepsilon_r = 2.1$, and variable substrate thickness, h=2 mm. The patch and the ground plane are implemented as the perfect conductors. To excite the antenna, a coaxial feed is introduced (Fig.1) modelled with the TLM compact wire model [24].

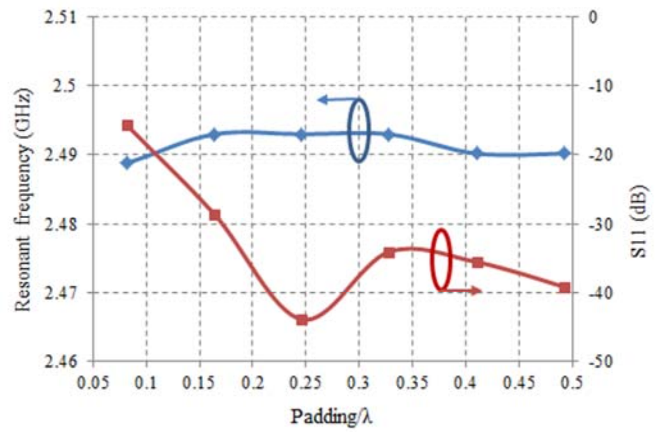
The antenna is bent over a cylinder of radius R, where the radius R is defined with reference to the patch as shown in Fig.1(b). The bending angle is also defined with reference to the patch dimensions so that $R(2\theta)$, is defined either with respect to the patch length (E-plane bending) or the patch width (H-plane bending). The antenna bent in the E-plane and sampled using the cylindrical mesh is shown in Fig.2. The size of the cylindrical node used in discretization is defined by $r\Delta\varphi = \Delta r = \Delta z = \Delta l$.

The cylindrical mesh can also be used to model a flat antenna when a sufficiently large bending radius is applied. The flat antenna is taken as a reference case against which the cylindrically bent antenna is compared. Namely, the flat antenna is realized in the cylindrical coordinate system by defining a very small bending angle, $2\theta = 0.1°$, which corresponds to the large radius i.e., $R = 22.63$ m. All simulations have been performed by an in-house TLM software.

The first issue to consider when modelling open problems is the size of computational box that can be defined as the free-space padding placed around the object under investigation. In the case of antenna, the padding needs to be placed at sufficient distance from antenna so that it does not interfere with antenna operation. The matched boundary conditions are placed on the computational box so that all outgoing waves are absorbed. To demonstrate the impact of the computational box on the results, the padding is assumed to range from 10 mm to 60 mm (e.g., 0.08λ - 0.5λ) where λ is the wavelength corresponding to the resonant frequency of 2.45 GHz. In order to improve the accuracy of the simulation and optimize computational resource a refined mesh is deployed around the antenna with Δl=1 mm for the cylindrical mesh and Δl=0.5 mm for the cubic mesh, whilst away from antenna the mesh is set to be Δl=1.5 mm and Δl=0.7 mm for the cylindrical and the cubic mesh, respectively. Fig.3. presents the resonant frequency and the S_{11} value at the resonant frequency for various padding values. Taking the resonant



(a)



(b)

Fig.3. Comparison of the resonant frequency and S_{11} parameter of the flat antenna with h = 2 mm substrate thickness for different padding values around the basic structure ranging from 10 mm to 60 mm (e.g., 0.08λ - 0.5λ): (a) the cylindrical mesh, (b) the cubic mesh.

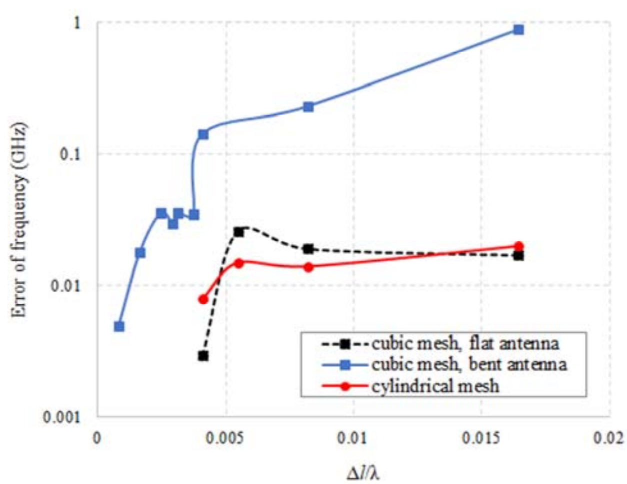


Fig.4. Illustration of the resonant frequency convergence with the mesh refinement when the cubic mesh is used for the flat antenna (light blue line), and for the bent antenna under the angle of 18° (blue line), and cylindrical mesh (red line) is used for the flat/bent antenna (Δl represents the observed cell size, and λ is the wavelength corresponding to the operating frequency).

frequency as more stringent criteria, Fig.3. shows that in both cases the results converge for padding of 0.4λ.

One of the most important issues in the modeling process is to ensure convergence of results with respect to the mesh discretization. Fig.4. compares the convergence of the resonant frequency with the mesh size for both the flat antenna and the antenna bent in the E-plane with a bending angle of $2\theta = 18°$ using both cubic and cylindrical meshes. A convergence error is calculated as the difference between two results obtained with successive discretization. The horizontal axis in Fig.4. represents a normalized mesh size with respect to the wavelength, $\Delta l/\lambda$, used within a refined box around the antenna. It is declared that the convergence is reached for errors below 0.01 GHz.

Fig.2. shows that in case of the flat antenna, convergence is observed for mesh sizes below 0.004 λ (e.g., 0.5 mm) for both the cubic and cylindrical meshes. However, in the case of the antenna curved by 18°, the convergence of the cubic mesh is much slower and is only reached for meshes finer than 0.0008 λ (e.g., 0.1 mm). This is due to the fact that the discretization error of the cubic mesh is significant and needs to be taken into account. In contrast, the convergence of the cylindrical mesh for modelling of cylindrically bent antennas is much smoother and is achieved for meshes 5 times larger than those required in the cubic mesh, i.e., 0.004 λ (0.5 mm). This proves that the major advantage of the cylindrical mesh for investigating models with different bending angles is that it allows for maintaining the same mesh size for all bending angles, ensuring exclusion of the influence of a different space discretization when performing an analysis of antenna bending impact on its performances, such as the case with the cubic mesh.

Since the mesh resolution directly affects the required memory and run-time, it is useful to assess computational requirements needed for each mesh. Table I compares the cell size, the total number of cells and a required computational memory of the meshes used for discretization of flat and bent antenna that result in the same accuracy as per Fig.3. It can be seen that, in the case of the flat antenna, both meshes are of the same discretization but the cubic mesh requires up to 3.5 times larger computational resources compared to the cylindrical mesh. In the case of bent antenna, the computational resource of the cubic mesh is 130 times bigger compared to the cylindrical mesh, for the same accuracy. This demonstrates a significant advantage of the cylindrical mesh for this particular application. Furthermore, whilst not as general as tetrahedral [25] or hexahedral meshes [26], it is expected that the cylindrical mesh would be still more computationally efficient.

TABLE I
THE COMPARISON OF COMPUTATIONAL RESOURCES BETWEEN THE CUBIC AND CYLINDRICAL MESH

Method	Cell size (refined mesh)	Number of nodes Nx×Ny×Nz for recTLM Nφ×Nr×Nz for cylTLM
Flat antenna		
recTLM	0.5 mm (0.004 λ)	180×380×360 ~25M
cylTLM	0.5 mm (0.004 λ)	311×80×311 ~7.7M
Bent antenna		
recTLM	0.1 mm (0.0008 λ)	650×1300×1300 ~1000M
cylTLM	0.5 mm(0.004λ)	311×80×311 ~7.7M

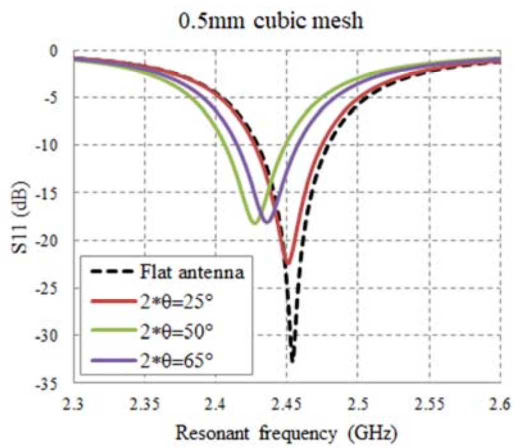
Fig.5. and Fig.6. show the impact of the choice of mesh discretization on the S_{11} parameter of the cylindrically bent antenna for a range of antennas bent over angles 2θ = 25, 50, and 65 degrees in case of the E-plane bending. In all cases the S_{11} parameter of the flat antenna is given for reference. Fig.5(a) compares the S_{11} parameters obtained using the 0.5 mm cubic mesh size. It can be seen that the resonant frequency of the antenna decreases with increasing the bending angle. Fig.5(b) shows the change of S_{11} parameter for different bending angles and for a cubic mesh size of 0.1 mm. Contrary to the results of Fig.5(a), Fig.5(b) shows that the resonant frequency increases with increasing bending angle. Comparing the value of the S_{11} resonance shift with the convergence accuracy of the cubic mesh it can be seen that they are of the same order. However, the convergence error of the 0.5 mm cubic mesh is higher than that of the 0.1 mm mesh, as reported in Fig.4, and large enough to influence the nature of the resonance shift.

Fig.6. compares the S_{11} values of a range of cylindrically bent antennas to those of the flat antenna obtained using a cylindrical mesh of mesh size 1.0 mm, (Fig.6(a)), and 0.5 mm (Fig.6(b)). Fig.6. shows that both meshes give the same behavior for the resonance shift and both agree well with the fine cubic mesh of 0.1 mm in Fig.6(b). In both cases the convergence error of the 1.0 mm and 0.5 mm cylindrical meshes was below 0.01 GHz and better than that of the fine cubic mesh. However, regardless of the cylindrical mesh size, this mesh does not introduce the discretization noise error and results in smooth discretization further adding to the accuracy of the simulations. Results of Fig.6. agree with the majority of reported literature stating that E-plane bending causes the shift of the antenna resonant frequency to higher frequencies [1,2,10-12,16]. Finally, Fig.5. demonstrates that the Cartesian discretization applied to curved antennas should be used carefully.

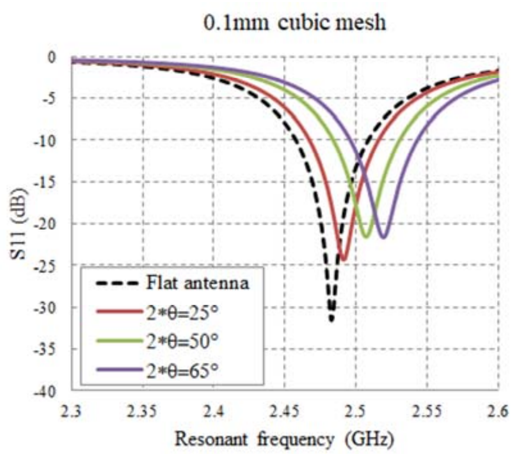
III. ANALYSIS OF CYLINDRICALLY BENT ANTENNAS

This section uses the cylindrical mesh to investigate the impact the bending deformation makes on antenna performance, namely the resonant frequency, the bandwidth and the radiation pattern of the antenna. Bending deformations in both E- and H-planes are considered for patch antennas designed on different substrate thicknesses namely h = {1, 2, 3} mm. The patch antenna dimensions are as described in Section III. All simulations are performed with a cylindrical mesh of cell size of 0.5 mm and a padding of 40 mm.

For reference, and in the context of better understanding the impact of bending on antenna performance, Table II presents how the resonant frequency and the antenna bandwidth of the flat antenna are affected by the substrate thickness. Results

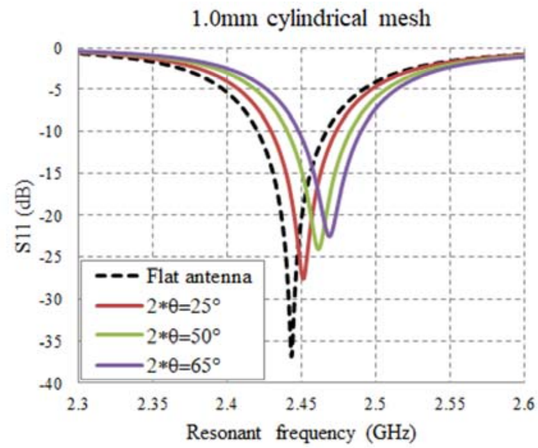


(a)



(b)

Fig.5. Comparison of S11 parameter of the flat antenna and antenna bent over an angle 2θ = 25, 50, and 65 degrees. Results are obtained using cubic mesh with a) 0.5 mm cell size, b) 0.1 mm cell size.



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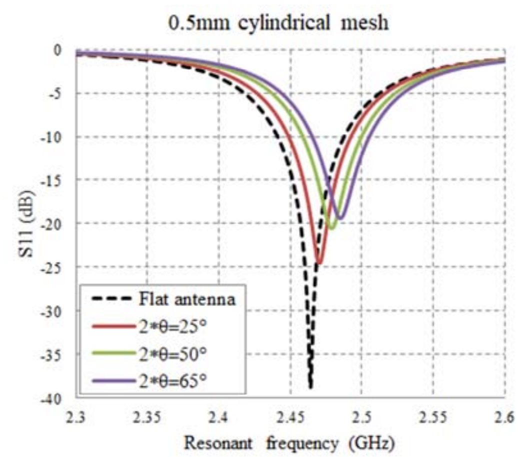


(b)

Fig.6. Comparison of S_{11} parameter of the flat antenna and antenna bent over an angle 2θ =25, 50 and 60 degrees. Results are obtained using cylindrical mesh (a) 1.0 mm cell size, and (b) 0.5 mm cell size.

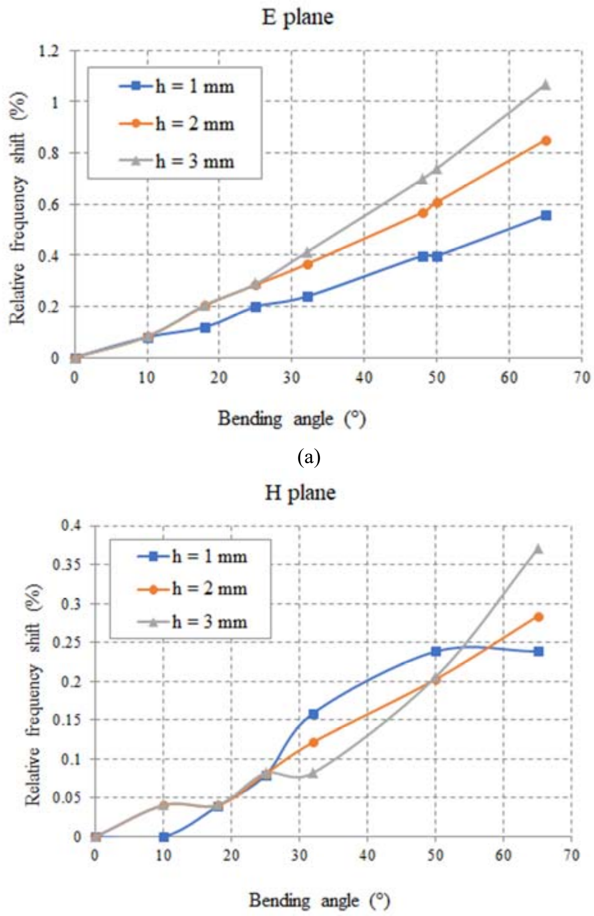
obtained using the cylindrical mesh are compared against analytical values obtained using the cavity model [26]. The results show that increasing the substrate thickness results in reduction of the resonant frequency which is in accordance with the analytical predictions. On the other hand, antennas with thicker substrate have larger bandwidth, since the bandwidth of the antenna is mainly dependent on the substrate dielectric constant and its thickness due to the fringing fields, which agrees with the theory [27].

Fig.7. shows the relative resonant frequency shift as a factor of bending angle for antennas designed on different substrate thicknesses. Fig.7(a) shows the relative frequency shift for bending in the E-plane and Fig.7(b) shows the same information for bending in the H-plane. Comparing Fig.7(a) and Fig.7(b) it can be seen that in the case of both E- and H-plane bending the antenna resonant frequency shifts towards higher frequencies and that the frequency shift is much greater when antenna is bent in the E-plane. This can be explained by the fact that the bending of the antenna along the length (E-plane) causes the effective resonant length and consequently effective dielectric constant to decrease resulting in the rise of the resonant frequency. As the length of the metallic patch directly defines the resonant frequency, the E-plane bending will be more critical for antenna operation. These results agree with other simulated and experimental results [1,2,10-12,16]. For the antenna fabricated on thicker substrates, the frequency shift is greater since the effective dielectric constant is experiencing larger change.

TABLE II
AN IMPACT OF THE SUBSTRATE THICKNESS ON THE RESONANT FREQUENCY AND THE BANDWIDTH OF THE FLAT ANTENNA

Substrate thickness (mm)	Analytical resonant frequency (GHz)	Simulated resonant frequency (GHz)	Bandwidth (MHz)
1.0	2.49	2.515	9
2.0	2.46	2.464	19
3.0	2.42	2.434	29

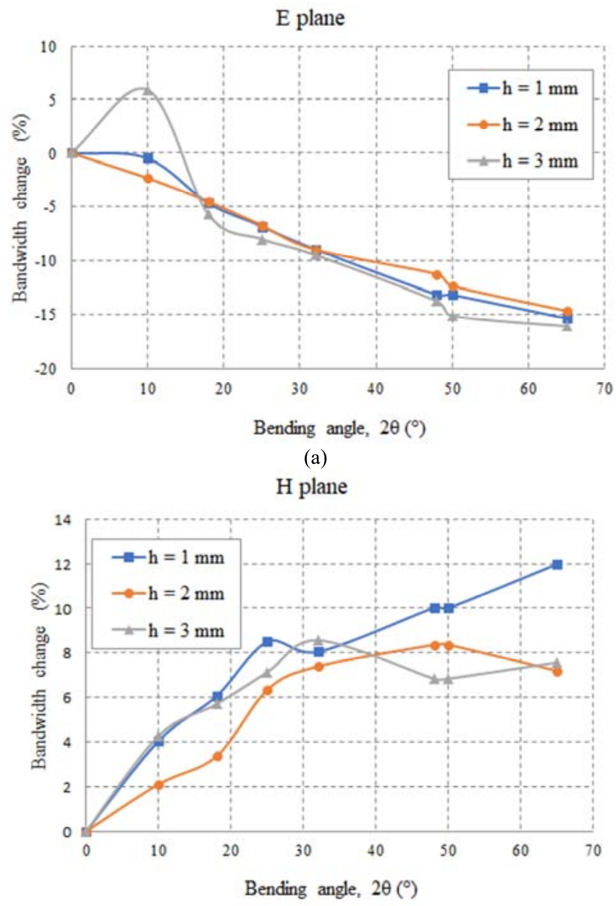
Fig.8. shows the impact of bending on the antenna bandwidth, for three different substrate thicknesses. Fig.8(a) shows the impact on the antenna bandwidth when the antenna is bent in the E-plane and Fig.8(b) shows the same for the antenna bent in the H-plane. In the case of E-plane bending, the fringing fields at radiating ends of antenna are in different planes, the radiated power is decreased and hence the



(a)

(b)

Fig.7. Relative resonant frequency shift for the case of a) E-plane bending and b) H-plane bending of antennas on the substrate of thickness h=1, 2, and 3 mm.



(a)

(b)

Fig.8. Bandwidth change for the case of a) E-plane bending and b) H-plane bending of antennas on the substrate thickness h=1, 2, and 3 mm.

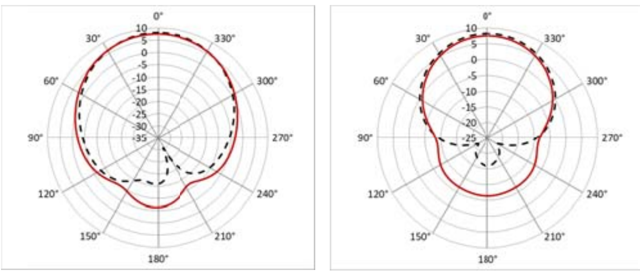
bandwidth is decreased as well. As can be seen from Fig.8(a), in the case of E-plane bending, the antenna bandwidth is decreased by up to 15% compared to the bandwidth of the flat antenna. For the H-plane bending, the fringing fields at radiating ends of the antenna are in the same plane and the bandwidth is increased mainly due to the effective dielectric constant decrease. Fig.8(b) predicts the increase in bandwidth of up to 12%. These results add further clarity to published results [10,11,13-16].

Fig.9(a) compares the normalized far field radiation pattern in the E- and H-planes of the flat antenna and the antenna bent by an angle of 65 degrees along its length (E-plane bending). It can be observed that bending along the E-plane of antenna causes broadening of the back lobe. Figs.9(b) compares the normalized far field radiation pattern in the E-plane and H-plane of the flat antenna and antenna bent in the H plane by an angle of 65^o. It can be seen that similar to E-plane bending, H-plane bending causes broadening of the back lobe. Phenomena in the far-field radiation pattern caused by the bending can be explained through disturbing radiation from two radiating slots under the bending. Namely, when the antenna is bent along the length (E-plane bending) the radiations from the slots are not in the same directions, whereas when the antenna is bent along the width (H-plane bending), the slots are curved but radiations remain in the same directions. Consequently, the radiation pattern is more affected when the antenna is bent along the length than along the width.

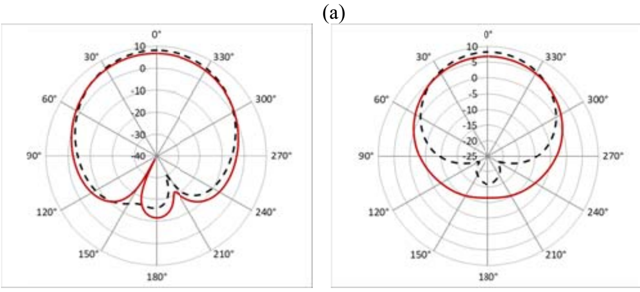
IV. Conclusion

This paper compares the effectiveness of two different discretization meshes, namely cubic and cylindrical, within the same time-domain numerical method that is applied to the problem of cylindrically bent antennas. Regardless of the mesh used the designer needs to ensure low convergence error so that inaccuracies of the mesh discretization do not interfere with the nature of simulated phenomena. It has been shown that erroneous conclusions can be reached when the cubic mesh of low accuracy is applied to study the impact of bending on antenna performance. The paper also demonstrates the applicability and computational efficiency of the structure aligned mesh, i.e. cylindrical mesh, to the problem of cylindrically bent antennas.

The cylindrical mesh is used to further analyze the impact of the bending on the 2.45 GHz textile antenna, namely its resonant frequency, the bandwidth, and the radiation pattern for a range of substrate thicknesses. It can be concluded that when antenna is exposed to bending deformation, the resonant frequency shifts to higher frequencies for both E- and H-plane bending. However, the shift is more pronounced in the case of



(a)



(b)

Fig.9. Comparison of the normalised radiation intensity in E- and H-plane of the antenna bent over 65^{o} (red lines) with the the radiation profiles of the flat antenna (black dashed lines), when the antenna is bent along (a) its length (E-plane bending), (b) its width (H-plane bending).

E-plane bending. This can be explained by the fact that bending reduces an effective length of the antenna resulting in a higher resonant frequency. The paper shows that the bending can significantly affect the antenna bandwidth; the bandwidth can be decreased by up to 15% but increased by up to 12% for the case of H-plane bending. The results show that antennas fabricated on thicker substrates are less stable under bending deformation as they experience a larger frequency shift and larger change in the bandwidth. Finally, it is shown that the bending disturbs a radiation pattern, a back lobe in particular, more for the case of the E-plane bending.

The results reported are valid for the case of concave bending of antenna in both E and H plane and further clarify the impact of a cylindrical bending on antenna characteristics.

Acknowledgment

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