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Application of mesh deformation for modeling of conformal RF components with 3D FEM

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Abstract—**In this paper, a method of analysis of conformal RF components has been proposed. In this approach, modeling of a curved structure is based on mesh deformation of planar objects rather than the construction of conformal geometry at CSG level. Since the model is represented as a 3D mesh, the deformation only requires the calculation of nodes position in the bent structure. The results of the proposed algorithm have been validated with simulation from other software and measurements, whereby method correctness has been confirmed.**

Index Terms— **simulation of flexible components, conformal antennas, mesh deformation**

I. Introduction

Conformal components and antennas find many applications in modern telecommunication systems. The low profile of the antenna allows usage in wireless communication with moving objects. Such devices are used in wearable [1], [2], automotive [3], [4], [5] and airborne [6], [7] applications. Moreover, their utilisation is reported in biomedical science [8], [9], [10] and energy harvesting [11]. Furthermore, they have found interest as a part of 5G and milimeter-wave systems [12], [13].

To meet the demands made of conformal structures, the method of electromagnetic simulation of such components is required. The analytical approaches were presented, but are mostly limited to antennas realized on cylindrical or conical geometries [14], [15].

In order to design components on an arbitrary surface, the techniques of electromagnetic simulation of conformal components made on the user-defined smooth surface are needed. Usually, to simulate such devices with 3D FEM, the layout of the planar structure is imprinted on a curved surface, then the mesh is generated, and the simulation is performed. However, in general, it is difficult to imprint the planar surface to arbitrary curved smooth, analytic surface.

In this paper, an alternative method of full-wave simulation of RF components, fabricated on arbitrary smooth surfaces is presented. The technique is based on mesh deformation of the planar structure, rather than directly modeling conformal objects and covering them with mesh. In this approach, the mesh of planar device has to be generated once; then, multiple conformal deformations could be performed using that initial mesh. In addition, the size of node-based FEM matrices remains the same, regardless of the deformation. This opens up new possibilities of efficient software-based optimization with FEM.

In the next section, the new algorithm is compared with the conventional CSG approach in more detail. In section III, numerical results of conformal antenna characteristics, obtained using simulation based on mesh projection are presented. In sections IV, further applications of algorithm are outlined, and all is concluded in section V.

II. Modeling and simulation of conformal structures

In general, the FEM analysis of the RF component begins with creating a CAD model of the device. Then the geometry is covered with mesh, in most cases, tetrahedral one. At this point, the structure is represented as a mesh - set of nodes and edges forming the unit elements, and in this form is passed to the FEM solver input, along with properly defined boundary conditions. In this section, the new method of modeling structures with conformal geometry is presented and compared with a conventional one.

A. Projection-based approach

In most cases of commercial software, model creation is based on a constructive solid geometry (CSG) technique [16]. The construction of specific objects by CSG is combining primitives, i.e., boxes, polyhedrons, cylinders, spheres, etc. using regularized Boolean operators. In order to achieve conformal 2D/3D shapes, this technique has to be supported by the projection of the arbitrary 2D object onto the equation-specified surface. With this, one could imprint a 2D, planar layout to the arbitrary surface, for example, imprint patch antenna on a curved substrate. Commonly used techniques of such imprinting are object wrapping (suitable for cylindrical objects) and parallel projection. The latter is more general, but it does not allow the user to control the dimensions (lengths) of the mapped 2D contour. The last stage of model construction is covering the resulting structure with mesh.

B. Mesh deformation approach

The projection algorithm is based on [17]. The initial steps of this approach are very similar to the previous one - the planar model is created using CSG. The key difference is the moment of structural deformation. In this method, instead of imprinting, the mesh is generated for the planar object (3D), and projection onto the user-defined surface is performed on the 3D mesh nodes rather than CSG model.

The proposed procedure of projection proceeds as follows: let the goal surface be described by function $z = f(x, y)$, and x_0, y_0 and z_0 are coordinates of nodes of the mesh of the initial, planar object. Now, point (x_p, y_p) located on surface $f(x, y)$ is calculated in such a way that the distances from point (x_p, y_p) to Z axis along X and Y axes, measured on the surface $f(x, y)$, are equal to x_0 and y_0 respectively. To compute these coordinates, the following set of equations has to be solved for each mesh point:

$$\int_0^{x_p} \sqrt{1 + \left(\frac{\partial f}{\partial x}\right)^2}\, dx = x_0 \tag{1}$$

$$\int_0^{y_p} \sqrt{1 + \left(\frac{\partial f}{\partial y}\right)^2}\, dy = y_0 \tag{2}$$

The purpose of this transformation is to preserve the distances between each mesh point of the planar structure during node projection onto the given surface. In effect, the lengths of edges in X, Y directions are preserved. The last step is calculation of the node position along Z axis, which is described by equation $z_p = f(x_p, y_p)$.

It can be noticed that for curved surfaces in 1D, like cylindrical surfaces, the proposed approach can be regarded as equivalent to wrapping operation. On the other hand, the proposed scheme is more general, since it can handle more general smooth 2D surfaces.

C. Simulation procedure

To perform electromagnetic analysis, the InventSim 3D FEM solver was used. The whole process begins with modeling the planar antenna structure and discretizing it with the 3D mesh. Then, the mesh is deformed by the projection algorithm described in the previous section. The final step is the simulation in InventSim based on the curved mesh. Both planar and curved meshes of the exemplary antenna are shown in Fig. 1.

Fig. 1. Mesh of planar antenna and the same mesh after projection onto conformal surface

III. Numerical results

To validate the mesh deformation approach, the analysis results were compared to simulation results that apply the imprinting. To obtain the reference data, an alternative commercial 3D FEM solver (HFSS) was used.

A. UWB antenna I

Antenna model is based on [18] and [19], with slight modifications. In order to reduce impact of feeding line on the radiation pattern, CPW has been replaced with coaxial line. Also, the antenna is projected onto cylinder lateral surface with 140 mm diameter. The dimensions of the planar structure and HFSS model are presented in fig. 2 and fig. 3 respectively. Thickness of the substrate is 0.254 mm and $\epsilon_r = 3.44$.

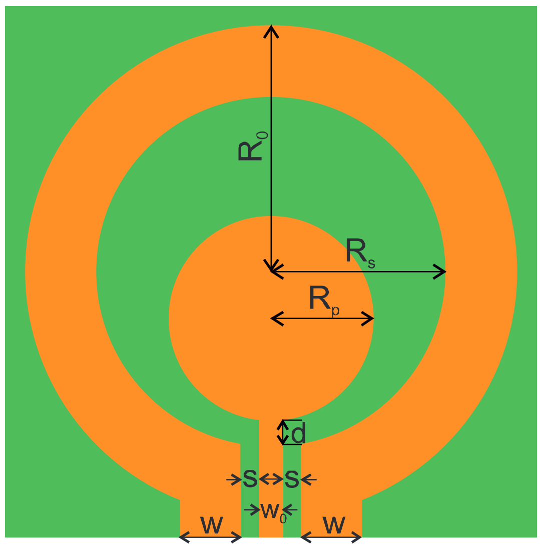

Fig. 2. Dimensions in mm of planar antenna: $w = 9$, $w_0 = 3.5$, $s = 0.15$, $d = 0.3$, $R_0 = 32.4$, $R_s = 23$, $R_p = 13.5$.

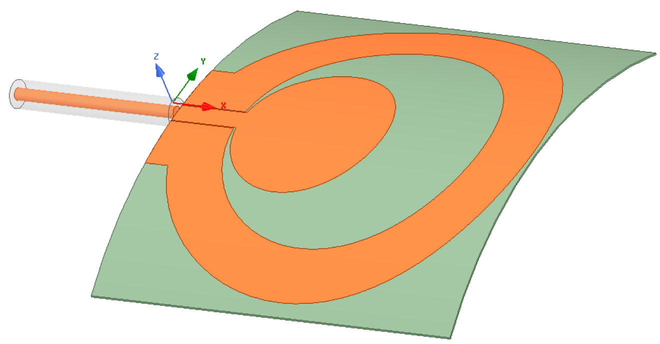

Fig. 3. HFSS model of conformal antenna

Fig. 4 presents comparison of $|S11|$ characteristics of the antenna from both approached. The results are convergent.

Radiation patterns obtained from both approaches at two frequencies are compared in figures 5 and 6. For frequency 3 GHz, radiation patterns are nearly identical. At higher

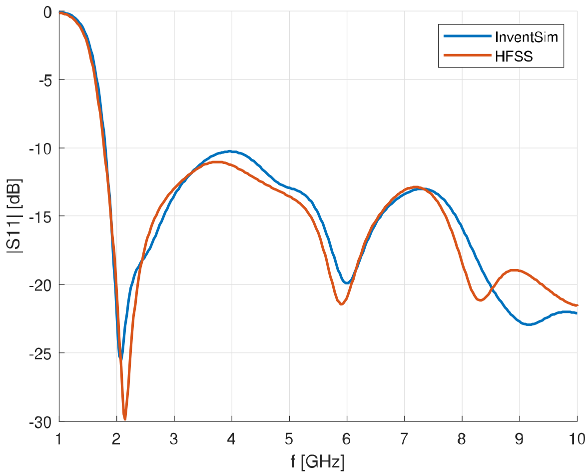

Fig. 4. $|S11|$ characteristic of UWB antenna I

frequency, the discrepancies could be noticed, but still, both characteristics are comparable.

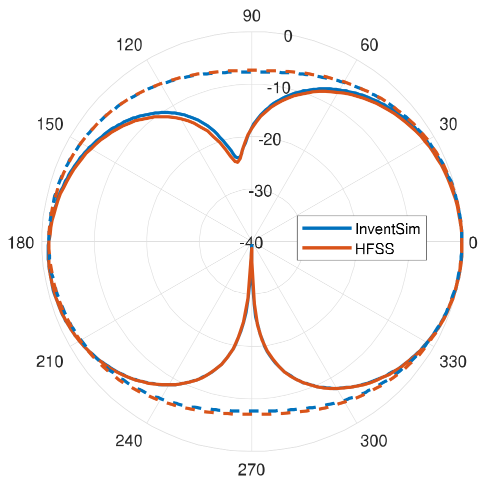

Fig. 5. Radiation pattern of UWB antenna I at 3 GHz. Solid lines - XZ plane, dashed line - YZ plane.

B. *UWB antenna II*

The antenna structure is based on [20] and shown in Fig. 7. Substrate thickness is 1.5 mm and $\epsilon_r = 2.65$. The antenna structure is projected onto lateral surface of cylinder with diameter equal to 40 mm. The HFSS model is presented in Fig. 8.

Despite minor resonance shifts, there is good level of accordance between S parameter characteristics (fig. 9).

In figures 10 and 11 radiation patterns obtained from InventSim and HFSS are presented. Similarly, as in the previous example, there is a good agreement between the results. However, the error level is higher, especially in YZ plane at frequency 7 GHz. It should be noted, that though these divergences, the main character of the radiation is still congruent.

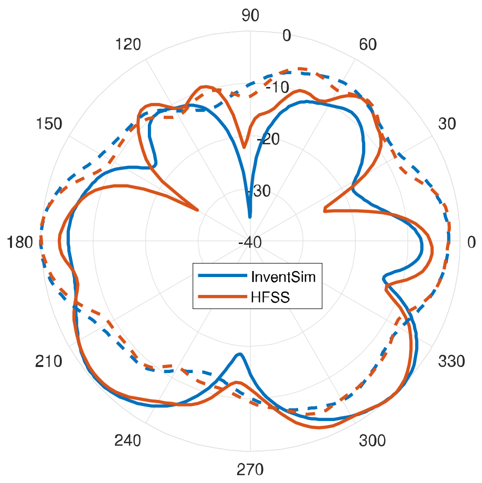

Fig. 6. Radiation pattern of UWB antenna I at 10 GHz. Solid lines - XZ plane, dashed line - YZ plane.

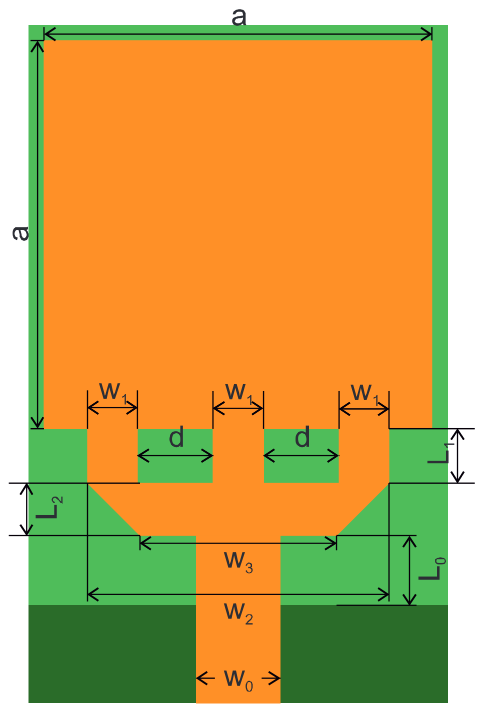

Fig. 7. Dimensions in mm of planar antenna: $a = 18.5$, $d = 3.35$, $w_0 = 4$, $w_1 = 1.2$, $w_2 = 10.3$, $w_3 = 8.6$, $L_0 = 3.7$, $L_1 = 1.3$, $L_2 = 1.2$.

IV. Further Applications

The presented simulation procedure can be applied to analyze conformal structures projected onto an arbitrary surface. The curvature can be equation-specified or be in the form of a surface interpolated from discrete points - for example, as output from a 3D object scanner.

As an example, the geometry of the conformal patch antenna on a complex, double-curved (in both X and Y axes) surface is presented in fig. 12. The analysis results of both, planar and conformal cases of the antenna are presented in figures 13 and 14. The bending of the antenna results in a resonance shift and

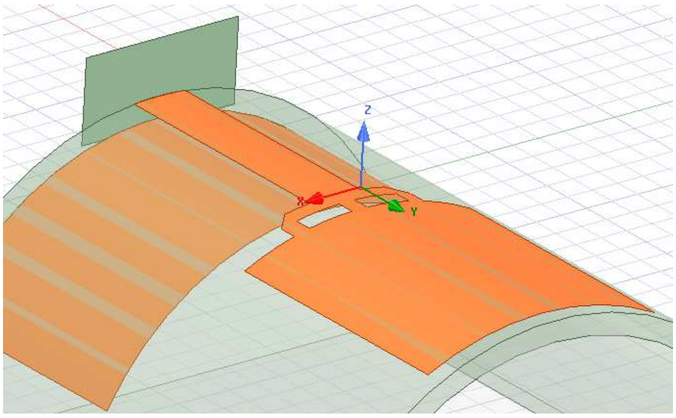

Fig. 8. HFSS model of conformal antenna

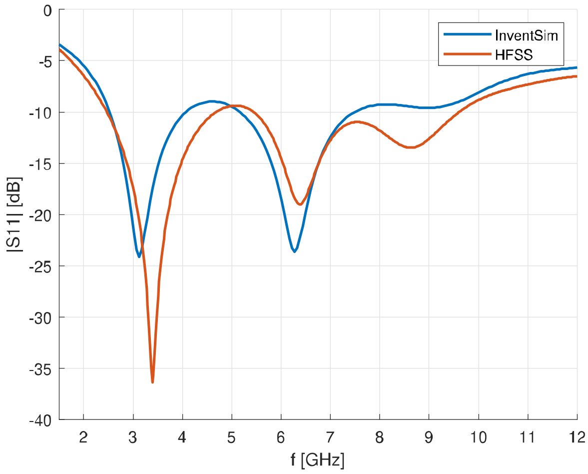

Fig. 9. $|S11|$ characteristic of UWB antenna II

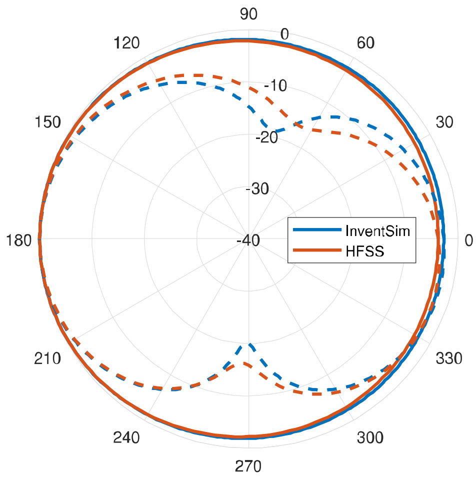

Fig. 10. Radiation pattern of UWB antenna II at 3 GHz. Solid lines - XZ plane, dashed lines - YZ plane.

tilt of 36° of the radiation pattern in XZ plane. In the next step of the design, the antenna length could be optimized to

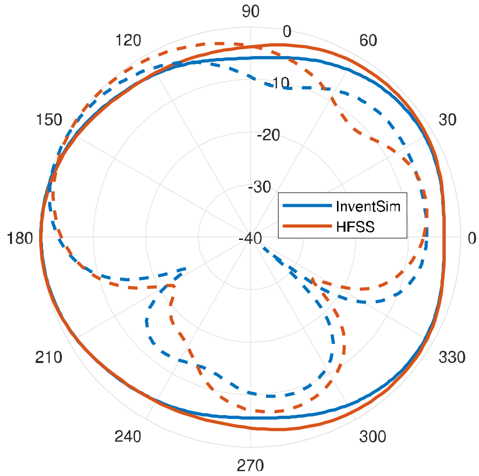

Fig. 11. Radiation pattern of UWB antenna II at 7 GHz. Solid lines - XZ plane, dashed lines - YZ plane.

achieve the required resonance frequency.

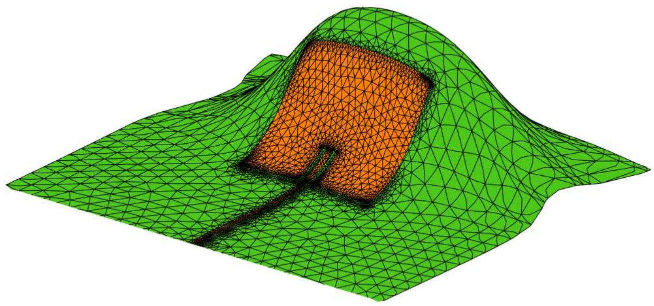

Fig. 12. Structure of conformal antenna

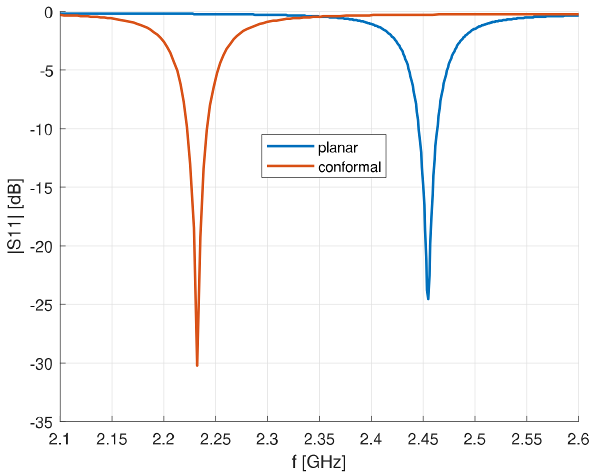

Fig. 13. Comparison of $|S11|$ characteristics

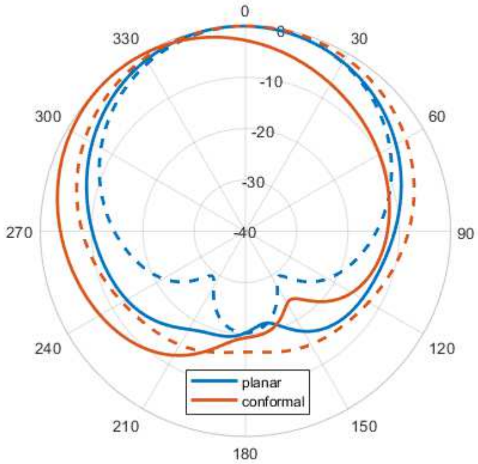

Fig. 14. Radiation patterns of the antennas at their resonance frequency. Solid lines - XZ plane, dashed lines - YZ plane.

V. Conclusion

The new method of modeling conformal structures has been used to analyse two antennas. The results have been compared with reference data, obtained from alternative software. In general, the simulated characteristics are convergent and satisfactory. Further experiments, including simulation and measurement of fabricated prototype devices are required to investigate the accuracy and possible further applications of presented approach.

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