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In this work a method for constructing wave propagation paths on aircraft modeled with nonuniform rational bi-cubic splines has been proposed and investigated. Procedures for dealing with artificial discontinuities due to geometric mis-matches of spline patches have been developed and implemented in numerical codes.

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Novel Techniques for Solving High-Frequency Scattering Problems on Complete Aircraft

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1 Introduction

In this work we investigated several geometrical issues arising in high-frequency electromagnetic (EM) calculations on aircraft modeled with nonuniform rational bi-cubic splines (NURBS). An aircraft model represented by NURBS consists of a collection of surface patches each of which is described by rational bi-cubic splines. Such representation of surfaces is widely accepted in design and manufacturing industries and utilization of the already existing models for electromagnetic analysis is a highly desirable alternative to the very expensive and time consuming task of building anew a suitable computational mesh. However, one of the main difficulties in modeling and computing wave propagation over aircraft represented by NURBS is connected with the fact that while each surface patch has a smooth parametrization, the overall smoothness may not be available because on typical models the patches do not match along their boundaries within the accuracy limits required for the EM analysis. In other words, such models have artificial discontinuities. Obviously, if a model is to be used for the EM analysis these discontinuities should be recognized and accounted for. Analytically, these discontinuities result in discontinuities in coefficients of differential equations describing the wave propagation.

A possible way to deal with this problem is to perform a pre-processing step on which a given model is modified so that the rather stringent geometric requirements are met. Unfortunately, very few techniques for performing such a step are currently available and in many cases an extensive manual and time-consuming effort for "healing" a model is required.

In this work we investigated an alternative strategy for dealing with this problem. In our approach, rather than performing an expensive general pre-processing step, we are recognizing such discontinuities within the EM analysis process and provide means for dealing with them. Specifically, for the particular problem of surface ray-tracing required for surface diffraction analysis we developed several techniques for continuing wave propagation paths (geodesics in the surface metrics) across the boundaries of patches. These techniques are based on application and extension of geometric results on manifolds with singular metrics [2], [3], [4]. An algorithm realizing this approach to ray-tracing has been also developed and implemented in a system of computer codes. The codes have been tested on some simple surfaces and on the fighter VFY 218 model in the IGES 128 format (see section 2 for details on this format). The results of the tests confirmed the validity of our approach.

Future work may be an expansion of the developed codes to include more complex propagation paths containing surface and spatial segments as well as edge and corner diffractions, reflections, etc. These developments, in conjunction with an implementation of the Geometric and Uniform Theories of Diffraction (GTD and UTD, respectively) based on the developed geometric computational techniques, should lead to a new set of computational codes providing better accuracy of high-frequency EM analysis than that available with the currently existing codes.

The theoretical results obtained under this effort are currently being prepared for publication.

2 IGES Format and Surfaces Represented by NURBS

A representation of surface data with NURBS can be organized in many different ways. In this work we utilized the representation provided by the so-called Initial Graphics Exchange Specification (IGES) format, version 5.3 [1]. The IGES format is a large collection of information structures for digital representation and exchange of product definition data, including curves and surfaces. This format evolved over a period of almost 20 years and it is accredited as an American National Standards Institute (ANSI) Standard. Because of the strong interest in utilizing aircraft models in IGES format by the Computational Electromagnetics community, it is important to investigate the issues of implementing wave propagation techniques on such models.

In the IGES format different data structures for describing the geometry of objects are distinguished by the "Entity Type Number". The specific IGES entity used in this work for aircraft model representation is the IGES 128. A complete description of all entities in the IGES can be found in [1].

In the IGES 128 format a surface is represented as an indexed collection of surface pieces each of which is a grid of surface patches constructed from rational functions. The locations of the nodes of the grid(s), the degrees of the polynomials defining the surface patches, and their corresponding coefficients are stored in the appropriate data structure. The format of the entity follows specific rules that must be used by an application in order to retrieve from a given data structure the required geometric and analytic information.

A complete description of a surface is provided by the parametric equations of a surface, that is, the coordinate functions describing the surface as a submanifold in R^3. In our case, the parametric equations of each surface patch are recovered from the IGES data structure describing the surface.

3 Geodesics on Surfaces Represented by NURBS

High frequency approximations require often the knowledge of surface geodesics along which surface waves propagate; see Kouyoumjian-Pathak-Burnside [5], Pathak-Wang [6] [7], [8], and other references there. For surfaces represented by NURBS, before one can proceed with the construction of surface geodesics, it is necessary to determine the coefficients of the differential equations defining the geodesics. These are constructed from the parametric equations of the surface as follows.

Let S be a surface in R^3 given as a collection of patches. Each patch is parametrized by coordinates (u,v) which are the Cartesian coordinates in a domain D on a u,v - plane. On each patch the surface is represented by

$$\mathbf{r}(u,v) = (x(u,v), y(u,v), z(u,v)), \quad (u,v) \in D, \tag{1}$$

where the functions $x(u,v)$, $y(u,v)$ and $z(u,v)$ are rational functions determined by the IGES data structure. The first fundamental form (that is, the metric) of S is a quadratic form

$$ds^2 = E(u,v)du^2 + 2F(u,v)dudv + G(u,v)dv^2,$$

where

$$E = \frac{\partial \mathbf{r}}{\partial u} \cdot \frac{\partial \mathbf{r}}{\partial u}, \quad F = \frac{\partial \mathbf{r}}{\partial u} \cdot \frac{\partial \mathbf{r}}{\partial v}, \quad G = \frac{\partial \mathbf{r}}{\partial v} \cdot \frac{\partial \mathbf{r}}{\partial v}.$$

Using the coefficients E, F and G the Christoffel symbols of the second kind are constructed according to the formulas:

$$\Gamma^1_{11} = \frac{GE_u - 2FF_u + FE_v}{2(EG - F^2)}, \quad \Gamma^2_{11} = \frac{2EF_u - EE_v - FE_u}{2(EG - F^2)}, \tag{2}$$

$$\Gamma^1_{12} = \frac{GE_v - FG_u}{2(EG - F^2)}, \quad \Gamma^2_{12} = \frac{GE_u - FE_v}{2(EG - F^2)}, \tag{3}$$

$$\Gamma^1_{22} = \frac{2GF_v - GG_u - FG_v}{2(EG - F^2)}, \quad \Gamma^2_{22} = \frac{EG_v - 2FF_v + FG_u}{2(EG - F^2)}, \tag{4}$$

and

$$\Gamma^1_{21} = \Gamma^1_{12}, \quad \Gamma^2_{21} = \Gamma^2_{12},$$

where $E_u, E_v, \ldots$ denote the corresponding partial derivatives.

The system of ordinary differential equations defining a geodesic is given by

$$u' = p, \quad v' = q, \tag{5}$$

$$p' = -\Gamma^1_{11}p^2 - 2\Gamma^1_{12}pq - \Gamma^1_{22}q^2, \quad q' = -\Gamma^2_{11}p^2 - 2\Gamma^2_{12}pq - \Gamma^2_{22}q^2. \tag{6}$$

Observe, that the coefficients of the system (5), (6) are computed only for a specific patch and will change when we move to a different patch. Obviously, in order for the

Christoffel symbols to remain continuous across the boundaries of adjacent patches, these patches must match up to the second order of smoothness. As it has been explained in the introduction, quite often, this condition is not satisfied and, consequently, the right hand side of (5) and the coefficients in (6) are discontinuous. We will return to this issue in the next section, after we complete the discussion of the initial conditions for the system (5), (6).

Different types of boundary value problems can be considered for the system (5), (6). For a point source of radiation on a surface it is natural to consider the initial boundary value problem (IVP) in which the location of the source and the direction of propagation are specified. Thus, the user must specify the initial point P on the surface (the wave launching point where the geodesic should start) and the initial direction T (of unit length) in which the geodesic should go.

The initial conditions require some explanations. The first difficulty is that, typically, the initial point is given as a point in R^3 (even if it is on the surface), but the system (5), (6) is in terms of the local coordinates u, v. Therefore, for a given initial point, say, X_0, Y_0, Z_0, one needs to determine

(a) the surface patch it belongs to and
(b) the local coordinates u_0, v_0 such that $X(u_0, v_0) = X_0, Y(u_0, v_0) = Y_0, Z(u_0, v_0) = Z_0$.

The step (a) is accomplished by a search algorithm and the step (b) by a gradient method.

Finally, we need to set up the initial direction in terms of local coordinates. Suppose the initial direction is given as a vector $T \in R^3$. Once the point (u_0, v_0) is known, the derivatives $\mathbf{r}_u(u_0, v_0)$ and $\mathbf{r}_v(u_0, v_0)$ can be computed. Then the vector T is decomposed in these two vectors and we obtain its corresponding component in required form. (To make sure that T is tangent to the surface, we take as T only the projection of the initially given vector onto the plane spanned by $\mathbf{r}_u(u_0, v_0)$ and $\mathbf{r}_v(u_0, v_0)$.) Further, T should be normalized to have unit length. The corresponding two numbers (that is, the coefficients p_0 and q_0 of the expansion of T in $\mathbf{r}_u(u_0, v_0)$ and $\mathbf{r}_v(u_0, v_0)$ provide the remaining initial conditions for the system (5), (6), that is,

$$p(u_0, v_0) = p_0, \tag{7}$$

$$q(u_0, v_0) = q_0. \tag{8}$$

4 Construction of Numerical Solutions to (5) - (8)

1. Let P be the patch containing the initial point u_0, v_0. On P the system (5) - (8) is solved by a high order ordinary differential equations solver. The solution (that is, the geodesic) is continued until it reaches the boundary of P. Let Q be the last point on the geodesic in patch P. In order to continue the geodesic past the boundary of that patch, we first identify the patch of the surface that also contains Q or, if such a patch can not be found, we identify the patch for which the distance to Q is minimal among all patches (except P). If this minimum is within the user specified error tolerance and if such patch is unique then we have a patch into which the geodesic is to be continued. If there are several patches on which the same minimal distance is realized, additional steps are required to make the proper selection. We will describe these steps below in subsection 2. If no suitable patch is identified the algorithm stops.

Suppose that the algorithm found a unique patch into which the geodesic should be continued. Denote this patch by P' and let Q' be the point on P' closest to Q (including the case when $Q \equiv Q'$.) The semi-tangent to the geodesic at the point Q (on the side of P) defines a direction T' in which the geodesic should be continued. If T' is tangent to P' at Q' then Q' and T' are taken as the new initial conditions in patch P'. The coefficients of the system (5) - (6) are redefined in this patch and a new piece of the geodesic is constructed.

If, however, the vector T' is not tangent to P', we perform the following operations. First, we check that the tangents to the boundary curves of P and P' passing through Q and Q', respectively, are parallel. If this is the case, then the vector T' with the base point Q' is rotated in the plane perpendicular to that tangent until it becomes tangent to the patch P'. If this is possible, then the corresponding new direction is the direction in which the geodesic is continued. This procedure implements the so-called "equal angle" condition based on geometric properties of geodesics on manifolds with singular metrics [2], [9]. It can be shown that this is the correct continuation of a geodesic in the presence of discontinuity. This procedure allows to handle also the case when the discontinuity is due to the presence of an actual edge (say, an edge of a wing on an aircraft).

If the tangents to the boundary curves of P and P' passing through Q and Q', respectively, are not parallel (within specified error tolerances) the algorithm stops.

2. Let us now return to the case when there is more than one patch at the same distance from Q. In this case, the surface has either a self-intersection, or it touches itself at Q, or the point Q is a corner point for several patches. The cases of a self-intersection and self-touching are not typical for aircraft surfaces and, for that reason, not considered. In the case where several patches have Q as their corner point the following procedure is used to identify the proper continuation of the geodesic. First, for each patch with the vertex Q we compute the surface angle between semi-tangents emanating from Q and tangent to the boundary curves emanating from Q. Let $K(Q)$ be the sum of these angles taken over all patches with the vertex Q. Let t be the vector tangent to the already constructed geodesic in patch P and directed "into" the patch P. Define a vector T' tangent to some patch adjacent to Q and such that the angle between t and T' measured on the surface consisting of patches adjacent to Q is equal $K(Q)/2$. Such a vector is uniquely defined and its direction is taken as the direction for continuing the geodesic. This procedure is also based on properties of geodesics on manifolds with singular metrics [2], [3]; see also .

In the beginning of the algorithm the user specifies the length of the required geodesic and the above steps are repeated until either the required length is attained or the algorithm stops because the surface discontinuities do not allow a reasonable continuation of the geodesic.

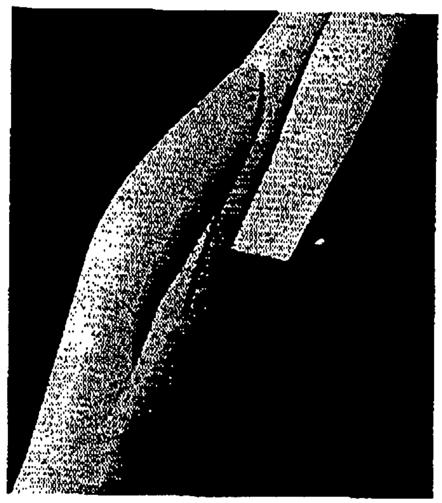

Figure 1: A propagation path on the VFY218 fighter modeled with NURBS

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