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A novel surface mesh deformation method for handling wing-fuselage intersections

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Abstract This paper describes a method for mesh adaptation in the presence of intersections, such as wing-fuselage. Automatic optimization tools, using Computational Fluid Dynamics (CFD) simulations, face the problem to adapt the computational grid upon deformations of the boundary surface. When mesh regeneration is not feasible, due to the high cost to build up the computational grid, mesh deformation techniques are considered a cheap approach to adapt the mesh to changes on the geometry. Mesh adaptation is a well-known subject in the literature; however, there is very little work which deals with moving intersections. Without a proper treatment of the intersections, the use of automatic optimization methods for aircraft design is limited to individual components. The proposed method takes advantage of the CAD description, which usually comes in the form of Non-Uniform Rational B-Splines (NURBS) patches. This paper describes an algorithm to recalculate the intersection line between two parametric surfaces. Then, the surface mesh is adapted to the moving intersection in parametric coordinates. Finally, the deformation is propagated through the volumetric mesh. The proposed method is tested with the DLR F6 wing-body configuration.

1. Introduction

In shape optimization problems,[1–3] the baseline geometry is modified in the search of an optimal shape. In each of the geometry modifications, it is required to update the mesh, and this can be achieved by using an automatic remeshing process. In the context of aircraft design, the grid generation of complex configurations involving several components is usually an expensive and time-consuming task that requires great expertise. In order to avoid the regeneration of the

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computational grid, automatic mesh deformation techniques[4,5] are considered a fast approach for small deformations, which is commonly employed in automatic optimization loops and aero-elastic simulations.

However, surface mesh deformation methods still suffer several limitations in the presence of moving intersections, such as wing-fuselage and wing-pylon-nacelle assemblies. Without a proper treatment of intersections, the use of automatic optimization methods for aircraft design is limited to individual components. In addition, once these components are assembled, the aerodynamic properties might be significantly different because of the fluid interaction between them.

In general, the intersection curve between two Non-Uniform Rational B-Splines (NURBS) surfaces cannot be determined analytically. There have been several attempts in the literature to address this problem. T-splines are designed to deal with trimming NURBS, although they might present difficulties to represent a watertight curve intersection.[6] The term "watertight" connotes no unwanted gaps or holes. The surface/surface intersection between NURBS is tackled in the research of Sederberg et al.[7] by using a moving algorithm: first, a local unit step direction H is determined by intersecting the tangent planes of the two surfaces, and guessing a new approximation $P1 = P0 + LH$, where L is determined from an adaptive method. $P1$ is approximated from a point at the intersection $P0$ and the direction tangent to both planes. In addition, in the research done by Gagnon and Zingg,[8] the geometries are defined analytically with watertight networks of surfaces and the approach is applied to a lift-constrained drag minimization of a conventional regional jet. Moreover, in the work of Hwang and Martins,[9] the approach is to model an aircraft as a union of untrimmed surfaces (i.e. surfaces with four topological edges). Regarding surface mesh deformation, different approaches are proposed to use spring/mass type idealization[10–12] or solving elasticity equations[13–15]. In this work, an adaptation based on the Laplacian field is suggested.

This method takes advantage of the CAD definition, in the form of NURBS surfaces, to recalculate the intersection, and therefore, requires deforming the NURBS along with the grid. This parametrization is widely supported by software tools, but for optimization applications, the final shape is strongly conditioned by the number and distribution of the control points. NURBS extracted directly from the CAD-file are unlikely suitable for optimization. Thus, a new NURBS needs to be generated, which still represents the original geometry within acceptable error margins, which is a time-consuming task that requires a great deal of expertise.

The above issue does not appear using differentiable volumetric methods, such as Free Form Deformation (FFD),[16] and its extension to volumetric B-splines control box.[17] The intersection between components is accurately calculated in each optimization step, while at the same time, the CAD file is preserved to easily share the geometry between software applications (for instance, in case of coupled fluid–structure optimization problems). After the computation of the intersection line, the surface mesh vertices are deformed by following their NURBS parametric coordinates, which have been previously obtained from the mesh generation application or calculated with an appropriate inversion point technique.[18,19] Finally, the surface grid is updated to match the moving intersection with a mesh deformation algorithm. Once the surface grid is properly adapted to the new configuration, a volumetric adaptation is employed to build the new computational grid.

The control box extends the FFD concept, using NURBS basis. This technique requires the additional effort of calculating the parametric coordinates from the spatial coordinates through an appropriate point inversion algorithm. However, the control box approach has important advantages over FFD, such as deformation locality, arbitrary setup of the control points, selection of the smoothness and the ability to choose the order of the interpolation, while achieving the same pleasing deformation characteristics as surface NURBS. Actually, the conventional FFD can be considered a subset of control box.

Additionally, some parameterizations can fuse components into the same description, so wing-fuselage surfaces are treated as a single entity with all the deformation being continuous and the intersection naturally adapted. However, there is an important advantage of describing specific components with a unique set of NURBS. Different aircraft components, such as wing, fuselage, nose and pylon, require different skills and expertise, and it is generally convenient to keep them intact while one component is optimized. For example, modifications of the wing should not modify the fuselage geometry. Without an underlying geometry, provided by NURBS, global deformations might result in unwanted modifications of other components.

This paper is structured as follows: the next section briefly introduces the mathematical background of NURBS. Then, Section 3 describes the proposed mesh adaptation strategy, giving details on the inversion point, intersection recalculation and surface deformation algorithms. Finally, the proposed strategy is applied to three different deformation scenarios (bump, rotation and displacement movements of the wing) of the DLR F6 wing-body configuration and an analysis of the performance and mesh quality metrics are provided in order to validate the approach. The DLR-F6, is a simplified wing-fuselage geometry which has been used for the validation of CFD codes at the AIAA sponsored Drag Prediction Workshops.

2. Mathematical background: Brief introduction to NURBS

NURBS are a standardized geometric description frequently employed by CAD applications to represent a surface skin. By incorporating the NURBS in the design loop, the effort to exchange information in a suitable format between different disciplines, such as aero-dynamic/structural analysis and post-processing tools, is significantly reduced.[8,9] The aerodynamic surface of an aircraft cannot be usually defined with a continuous shape for the whole geometry, and therefore, several NURBS patches have to be employed to assemble the different sections defining intersections and continuity conditions.

From the mathematical point of view, NURBS surfaces[20] are parametric representations defined as

$$S(\xi,\eta)=\frac{\sum_i^N\sum_j^M U_i^p(\xi)V_j^q(\eta)w_{ij}C_{ij}}{\sum_i^N\sum_j^M U_i^p(\xi)V_j^q(\eta)w_{ij}} \tag{1}$$

where $\{\xi,\eta\}$ are the parametric coordinates, U and V the basis functions of orders p and q respectively, C_{ij} the control points, and w_{ij} the weights. One of the most effective methods to calculate the basis functions is through a recursive algorithm,