Aerospace Science and Technology 59 (2016) 172–182

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

An unstructured quadrilateral mesh generation algorithm for aircraft structures

John T. Hwang *, Joaquim R.R.A. Martins

Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI 48109, United States

ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form 18 July 2016
Accepted 9 October 2016
Available online 28 October 2016

Keywords:
Aircraft design
Mesh generation
Aerostructural optimization
Structural optimization
Elliptical smoothing
Finite-element analysis

ABSTRACT

Because commercial aircraft are built with thin-walled structures, their structural performance is well-modeled using shell-element meshes. However, creating these meshes for the full aircraft configuration can be challenging and presents a bottleneck in the design process, especially in a configuration-level design space. This paper presents an algorithm that automatically creates unstructured quadrilateral meshes for the full airframe based on just the description of the desired structural members. The approach consists in representing each node in the mesh as a linear combination of points on the geometry so that the structural mesh morphs as the geometry changes, as it would, for example, in aerostructural optimization. The algorithm divides the aircraft skin into 4-sided domains based on the underlying *B*-spline representation of the geometry. It meshes each domain independently using an algorithm based on constrained Delaunay triangulation, triangle merging and splitting to obtain a quadrilateral mesh, and elliptical smoothing. Examples of full-configuration structural meshes are provided, and a mesh convergence study is performed to show that element quality is maintained as the structural mesh is refined. The algorithm is available as part of the open-source aircraft geometry tool suite, GeoMACH.

1. Introduction

The commercial aviation industry faces a pressing need to find ways to reduce aircraft fuel burn given the continued growth of air traffic [1], and rising environmental concerns. This has led to research into new aircraft configurations that deviate significantly from the cylindrical tube-and-wing design that has been used for over half a century, with the hopes of achieving revolutionary breakthroughs in fuel efficiency and in other metrics of interest such as noise. Since there is a lack of knowledge and data on unconventional configurations, there is a need for higher fidelity computational models that can be deployed quickly.

Current aircraft design processes, however, do not take full advantage of computational design tools. Early on in the design process, high-level design decisions are made with the help of relatively low-fidelity and low-accuracy models. This is because high-fidelity models are not well-suited to handle the range of designs considered in conceptual design. As the high-level aspects of the design become frozen—e.g., the placement of the engines—higher-fidelity models are gradually introduced to resolve the finer design parameters—e.g., the shape of structural ribs in the wing. This approach is not ideal, because the lowest-accuracy models are used earlier in the design process when the design decisions are the most important. Therefore, it is beneficial to bring higher-fidelity models earlier in the aircraft design process without sacrificing automation, usability, and computational time.

One area in which high-fidelity computational tools can make an impact is the design of the airframe—i.e., the structure of the aircraft. In airframe design, the dominant considerations are the aerodynamic shape and structural layout, which are intrinsically coupled. As an example, thinner and longer wings are beneficial for aerodynamics because they have lower drag, but they also result in more structural weight per unit wing area due to the higher bending stresses they must withstand. Moreover, with these thin and flexible wings, the aerodynamic loads that produce lift cause the wing to twist, which in turn increases the aerodynamic loads, so there is a strong coupling between these disciplines.

High-fidelity aerostructural optimization addresses this coupling by simultaneously optimizing the aerodynamic shape of the airframe and the sizing of the structural members [2,3]. This leads to at least $\mathcal{O}(100)$ design variables that must be optimized. There can also be thousands or more structural failure constraints, but these can be reduced to a single or a small number using constraint aggregation methods, such as the Kreisselmeier–Steinhauser

* Corresponding author.
E-mail addresses: hwangjt@umich.edu (J.T. Hwang), jrram@umich.edu (J.R.R.A. Martins).

http://dx.doi.org/10.1016/j.ast.2016.10.010

functional [4,5]. At this scale, gradient-based optimization is the only feasible approach [6,7], especially given the large computational cost of a structural or aerostructural simulation. For derivative computation, the adjoint method is the best choice in terms of efficiency for most problems because it computes all the derivatives at a computational cost nearly independent of the number of design variables.

For high-fidelity structural modeling and design, which is the focus of this paper, the common approach is to use a shell-element model. Aircraft are well-represented by shell elements because the structural members in aircraft wings and fuselages are in general very thin due to the premium placed on weight reduction. Using these shell elements, it is possible to model the ribs, stringers, spars, and stiffeners in the wings, as well as floor beams, frames, longerons, and bulkheads in the fuselage. The shell elements carry bending, twisting, axial, and shear loads.

One of the bottlenecks in airframe structural analysis is the construction of the structural mesh, which typically requires extensive manual effort and a high level of expertise. Meshing tools aim to alleviate this bottleneck. Given the overarching motivation for this paper—the rapid design and evaluation of unconventional aircraft configurations—there are four requirements for such a structural meshing tool. First, the structural mesh should be global to enable quantitative trade studies comparing configurations; that is, the mesh should model the full configuration (not just the wing), and there should not be separate, disconnected meshes for different aircraft components. Second, the mesh generation should be automatic so that given a description of the desired structural members, number and location of ribs, placement of spars, *etc.*, the mesh should be created without any additional manual effort. Third, the mesh should be computed as a function of shape design variables because for aerostructural design and optimization, shape changes must automatically morph the structural mesh. Fourth, the mesh definition should be differentiable, and the computation of the derivatives of the structural mesh coordinates with respect to the shape design variables should be efficient. Existing aircraft structural meshing tools do not satisfy all four requirements; some mesh only the wing [e.g., 8], some lack automation because they use an external tool to generate an unstructured quad mesh [e.g., 9], and others do not compute the mesh as a differentiable function of shape changes [e.g., 10].

There are additional application-specific requirements that we have not addressed because our primary focus is on the four fundamental requirements listed above. One such requirement is to be able to handle the parametrization of the composite layup [11, 12]. The modeling of the composite layup in each element is something that can be handled by a separate tool that takes the generated structural mesh as an input. Another requirement is multidisciplinary data transfer, especially the transfer of displacements and loads to and from computational fluid dynamics (CFD) analysis. However, it is possible to use a general load and displacement transfer algorithm that is independent of the structural mesh [13,2]. Another application-specific requirement is the modeling of control surface deflections, which is limited when using structured multi-block CFD, but is possible when approximating the control surfaces as morphing surfaces with a continuous trailing edge [14].

In this paper, we present an automatic unstructured quadrilateral mesh generation algorithm for aircraft structures that uniquely satisfies the four requirements mentioned above. The algorithm starts with a B-spline surface geometry representation and a list of requested structural members defined in terms of parametric locations on the surfaces. It then splits the geometry into domains, meshes each domain independently using constrained Delaunay triangulation (CDT) as well as merging and splitting operations, and then applies Laplacian smoothing as a final step.

The paper proceeds as follows. We first present the overall approach, discussing the geometry representation details, computation of the structural mesh, and the interface through which the requested structural members are specified. Next, we present the actual mesh generation algorithm, which divides into the global algorithm at the configuration level and a local mesh generation algorithm. Finally, we present results, including aircraft structural meshes created using the proposed algorithm.

2. Approach

In this section, we present the overall approach for the structural mesh computation. More specifically, we describe the assumed form of the geometry representation for the aircraft outer mold line (OML), explain how the structural nodes are computed from the geometry using a linear map, and then discuss how a user would specify the desired structural members.

For the results in this paper, we use the geometry-centric MDO of aircraft configurations with high fidelity (GeoMACH) tool suite [15,16]. GeoMACH is an open-source software library that models aircraft geometries using a patchwork of untrimmed B-spline surfaces, and includes an aircraft parametrization to support high-fidelity aircraft shape design optimization. The structural mesh generation algorithm developed here is part of GeoMACH, which is available through an open source license.[1]

2.1. Geometry representation

The only requirements on the OML geometry representation are that it is continuous and watertight. As mentioned previously, we use the geometry modeler in the GeoMACH tool suite for the figures presented in this paper. GeoMACH represents the geometry using untrimmed B-spline surfaces, though this is not the only choice with which the structural mesh generation algorithm would work. B-splines are piecewise polynomials used frequently in computer-aided design because of their favorable mathematical properties: compact support for a desired order and smoothness, and flexibility in terms of the number of control points and polynomial degree. B-spline surfaces are tensor products of B-spline curves that maintain the advantages of smoothness and sparsity. Fig. 1(a) illustrates how a conventional wing–body–tail aircraft geometry can be constructed with 4-sided B-spline surfaces.

An important feature of the geometry modeler is the ability to perform point-to-surface projections. These are required so that we can evaluate surface nodes for modeling the aircraft skin and for interpolating interior nodes. For the projections, the B-spline implementation in GeoMACH performs a Newton search to find the parametric coordinates (u, v) on the surface that yield the closest point to the given point that we are projecting. Since this procedure can fail in some cases, the algorithm first computes a brute-force closest-point search on a structured discretization of the surface, to be used as the initial point for the Newton search and as an alternative in case the Newton search does not converge. To handle cases in which the closest point is on one of the surface edges, there are provisions during the iteration loop to detect such a case and exit. This projection algorithm occurs at the individual surface level, so in general, all the B-spline surfaces that make up a geometry must be searched to find the closest point on the geometry to a given point. However, in the current application, only the small number of B-spline surfaces that comprise the aircraft component of interest (e.g., the upper surface of the wing) must be searched, since the relevant component is known for a given structural node.

[1] https://github.com/hwangjt/GeoMACH.