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Three-dimensional structural topology optimization of aerial vehicles under aerodynamic loads

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ABSTRACT

A previously developed density distribution-based structural topology optimization algorithm coupled with a Computational Fluid Dynamics (CFD) solver for aerodynamic force predictions is extended to solve large-scale problems to reveal inner structural details of a wing wholly rather than some specific regions. Resorting to an iterative conjugate gradient algorithm for the solution of the structural equilibrium equations needed at each step of the topology optimizations allowed the solution of larger size problems, which could not be handled previously with a direct equation solver. Both the topology optimization and CFD codes are parallelized to obtain faster solutions. Because of the complexity of the computed aerodynamic loads, a case study involving optimization of the inner structure of the wing of an unmanned aerial vehicle (UAV) led to topologies, which could not be obtained by intuition alone. Post-processing features specifically tailored for visualizing computed topologies proved to be good design tools in the hands of designers for identifying complex structural components.

1. Introduction

Determining the right topology for a load bearing structure, i.e., finding an optimum distribution of materials and placement of structural components over a structure are very important in terms of efficiency and cost. The traditional approaches of structural topology design were based on the experience, intuition and creativity of designers. In most cases, topology of existing structures were emulated or improvised. However, for complex structures, there is a need for more systematic approaches. When, a systematic optimization method is used during the conceptual design of a structure, major savings may be achieved from the amount of material and weight. Especially in automotive and aerospace industries, since there is always a need for reduced weight and savings in materials for efficiency and cost, the optimization is even more important. Because of that, the use of topology optimization methods has increased during the recent years. Since they offer many more useful alternatives in the hands of designers, intense research is continuing in this area. With the tools developed, the designers can use their experience and creativity for testing their new ideas.

Today, structural topology optimizations are mostly done using the finite element method because of its generality. For optimization process, there are two broad approaches: (1) *Microstructural approach* and (2) *Macrostructural approach*. A good review of these two approaches is given by Eschenauer ve Olhoff [1].

In this paper, we use the *microstructural approach* because of its versatility. This approach is also known as *materials or density distribution method* in the literature. In this method, the geometry of the optimum topology evolves by systematically computing a non-dimensional material density ρ_e in each finite element, which varies from zero to one to match a given volume reduction (volume fraction) of an initially defined design space. The element structural stiffness matrix denoted as k_{ij}^e is assumed to be linearly proportional to density. The density represents the volume fraction of the element. Thus, as density approaches to zero, so does the element stiffness, as a result an empty region is formed. Conversely, in regions where the density becomes one, the full stiffness of the material is fully reached, thus a fully solid region is formed. In regions where density varies between zero and one, a non-homogeneous region is formed. To enforce formation of distinct empty and solid regions, a penalty constant n greater than one is introduced to the optimization scheme as a power of density as in ρ_e^n for magnification of differences between low and high values of density.

The density distribution method was proposed for the first time by Bendsoe and Kikuchi [2] as a topology optimization method. A

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treatise on the widespread applications of the method is due to Bendsoe and Sigmund [3]. An interesting feature of the density distribution method is that, while it brings out the topology of the structure in macroscopic level, it also provides the distribution of the material density in microscopic level. Thus, it suggests a design for gradation of the material properties for a penalty constant with value of one, which may be important in some complex structures. While this is beyond the scope of our present study, it brings out the possibility for designing exotic composite materials as well. For slender (thin and long) structures, where the areas covered are large compared to the volume of the material, typically grid- and truss-type structures evolve with this method with penalty constants above one. One disadvantage of this method is that, since solid and empty parts are formed in a pixel format, there is a need for very dense meshes, which means more computation time and more memory are needed. Another disadvantage is the need to solve for large size structural equilibrium equations at each step of optimization, which are nearly ill-conditioned since the density values vary between zero and one. This requires preconditioning of the structural stiffness matrix for correct solution of the equations. Moreover, for real type applications, parallelization is a must for computing time as well as memory requirements.

Earlier parallel applications of topology optimization are due to Borvall and Petersson [4] and Vegamanti and Lawrence [5], who have used domain decomposition method for large-scale applications with good parallel performances obtained. Their applications were restricted to simple loading structures with unidimensional loads. Since weight reduction is of importance for aerial vehicles, topology optimization provides many benefits in the design of aircraft wings. The problem has been studied by several researchers in the past. For example, Rao, et al. [6] studied a wing case by considering both aerodynamic and engine loads. Their results showed that complex topologies might be obtained, when no constraints are introduced for a priori placement of spars and outer shells. They were able to obtain more traditional topologies when constraints were introduced, such as placing spars at different locations a priori. However, the aerodynamic loads used were based on a simplified lattice method, with significant deviations from more accurate realistic CFD solutions leading to inaccurate pressure distributions over the wing. Especially the pressures computed at leading and trailing edges were in error, which affect the results rather significantly. Other applications of the density distribution method to optimization of aircraft wings may be found in Refs. [7,8]. A good review of aeroelastic optimization can be found in Guruswamy and Obayashi [9].

2. Present work

Our emphasis here has been on coupling CFD solutions with the structural optimization problem to study the impact of aerodynamic loads in shaping the inner wing topologies. To achieve this we resorted to parallel computing as a tool to allow us to solve large-scale problems. Because the aerodynamic loading structure is rather complex and multidimensional, the optimization of wing structure is challenging. To do that we have chosen to utilize realistic CFD solutions under operating conditions and transfer the CFD pressures computed on wing surfaces to the structural mesh accurately and conveniently as aerodynamic forces. In a recent work, we have developed a parallelized structural topology optimization code to optimize the rib-structures of an aircraft wing under conventional fixed spar location placement approach under aerodynamic loads [10], which may be the preferred approach for conventional aircraft design considering manufacturing restrictions. Unlike in the present work, whole inner structural details of a wing have been optimized to reveal unconventional rib and spar shapes for the first time. For optimizations, the minimum compliance energy method [3] was used. This approach, starting with a solid wing profile determined an optimum distribution of the ribs inside the wing surface based on the choice of spars extending along the wingspan. The aerodynamic loads, computed under extreme flight conditions were delivered from the parallelized Computational Fluid Dynamics (CFD) module of our proprietary software CAEeda™ [11] to the surface of the wing. The optimization module, which is also parallelized, determined the optimum topology for the ribs under the aerodynamic loads received. For transfer of pressure forces from the CFD module to the topology optimizer module, the code- and mesh-coupling module SINeda of CAEeda™ was used [12].

In the earlier version of our topology optimizer [10], we used an open access direct equation solver, MUMPS [13], and its sparse matrix storage and parallelization scheme for solving the system of equations. This scheme proved to give satisfactory results for moderate size problems only, because as the size of the problem increased, the scalability was lost and the memory limits were reached for storage of the coefficient matrix. This restricted the size of the problem to be solved. As a result, the applications were restricted to moderate scale problems. To circumvent this, we have explored other options and as our parallel solver we have decided to use PETSc library (The Portable Extensible Toolkit for Scientific Computations) developed at Argonne National Laboratory [14]. PETSc is particularly rich in the choice of equation solvers and has several parallel iterative solvers in its library, among which we have chosen the *symmetric conjugate gradient method*. As matrix pre-conditioner, the *block-Jacobi method* was used, which is a *diagonal-matrix preconditioner* in block form suitable for parallel computing. This allowed us to solve large-scale three-dimensional problems, which we were not previously able to.

As an example case, topology optimization of a hypothetical unmanned aerial vehicle (UAV) is considered. Since weight is of utmost importance for especially High Altitude Long Endurance (HALE) type or mini and micro UAVs, the selection of minimum weight optimum topology is very crucial. Especially for mini and micro UAVs, manufacturing of complex geometries is affordable and less difficult, because of the relative ease of shaping and manufacturing of parts composed of advanced materials. Removing the manufacturing constraints in topology optimization of such vehicles here resulted with highly complex, yet interesting topologies, which could not be predicted by intuition alone, as will be demonstrated in Section 6.

3. Formulation

Since for the problem at hand, both flow analysis and topology optimizations are needed, we briefly describe the formulations used for both here.

3.1. Formulation of the flow analysis problem

For topology optimization of full three-dimensional wings, our previously developed CFD code FAPeda™ [15,16] was used to calculate the aerodynamic loads. This code is based on an unstructured cell-centered tetrahedral finite volume formulation. It solves compressible full Navier–Stokes equations with Spalart–Allmaras turbulence model [17]. For time-dependent calculations, backward Euler implicit time-integration scheme is used. Parallelization is based on a domain-decomposition method with one-cell overlaps for information exchange between subdomains [15]. For low Mach number and nearly-incompressible flows ($M < 0.3$), an artificial