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Concurrent aerostructural topology optimization of a wing box

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ABSTRACT

This paper presents a novel multidisciplinary framework for performing shape and topology optimization of a flexible wing structure. The topology optimization is integrated into a multidisciplinary algorithm in which both the aerodynamic shape and the structural topology are optimized concurrently using gradient-based optimization. The optimization results were compared with the results of a sequential procedure in which the aerodynamic shape was optimized separately and then used as a fixed design feature in a subsequent structural optimization. The results show that the concurrent approach offers a significant advantage, as this design achieved 42% less drag than the sequentially optimized wing.

1. Introduction

Aircraft design is a complex, multidisciplinary endeavor that places unique and aggressive demands on the engineers and scientists involved. This is especially true in the case of aircraft wing design. Historically, the need for light-weight, multifunctional aerospace structures has pushed the limits of the available materials and technology. As a result, numerical analysis and optimization methods have long played a major role in aircraft design, both in industry and among academic researchers. Over the last decade, topology optimization has emerged as one of several optimization techniques being used by most of the major aircraft manufacturers due to its ability to generate light-weight conceptual designs [1–4].

Perhaps the most prominent example of topology optimization for aircraft design is that of the Airbus A380, where topology optimization was used to optimize inboard fixed leading edge ribs as well as the fuselage door intercoastals [1]. For the wingbox ribs, engineers minimized structural compliance subject to fixed aerodynamic loading. The resulting structural layout was then refined using sizing and shape optimization. It is estimated that the use of topology optimization led to an overall weight savings of 1000 kg per aircraft [2]. More recently, Bombardier has also begun incorporating topology optimization into the premilinary design of airplane structures. For one study published in 2007 [3], Bombardier engineers satisfied the aerodynamic design requirements by selecting 20 criticial aerodynamic load cases that were used as design loads for two-dimensional optimization of wingbox rib topologies. A similar procedure has also been adopted by Boeing for the design of the leading edge wingbox ribs used in the 787 Dreamliner. Here, the combination of topolopgy optimization during the premilinary design phase, together with subsequent sizing and shape optimization, resulted in a leading edge structure that was 24–45% lighter than that of the 777 aircraft [4].

Although aircraft companies rarely publish the details of their design procedures [5], there is little evidence to suggest that any of the major aircraft manufacturers have incorporated multidisciplinary design optimization (MDO) techniques into the preliminary design optimization process on any significant scale. One of the few examples came in the form of a NASA study that presented results from a high-fidelity aerostructural analysis software system and introduced a framework for incorporating this software into a multidisciplinary optimization system [6]. By contrast, the typical airframe design cycle practiced in industry involves a sequential procedure that begins with a pure aerodynamic shape optimization. For this step, many aircraft manufacturers have used the "FLO" software [7], which includes a series of codes for performing computational fluid dynamics (CFD) analysis and computing shape sensitivities. This procedure is then followed by a refinement of the structural design using loads based on the aerodynamically optimized shape.

True multidisciplinary optimization for the design of aerospace structures continues to be confined mainly to academic research, where many researchers have published studies showing the use of fully coupled aerostructural analysis in their design optimization algorithms [8,9]. There have also been several examples of researchers using combining topology optimization with coupled

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aerostructural analysis. In their 2004 article, Maute and Allen [10] optimized the conceptual structural layout of a wing planform. Treating the wing as a flat plate, they used topology optimization to determine the location of a series of stiffeners. Here the mass was minimized subject to constraints on lift, drag, and tip deflection. In this example, the aerodynamic loads were coupled to the structural deflection. The resulting coupled aerostructural system was solved using a Newton-type method, with an adjoint method used to compute the derivatives. A subsequent paper, coauthored by Maute and Reich [11], used a similar aerostructural framework for optimizing the material distribution and the placement of actuators inside a quasi-three-dimensional morphing airfoil in order to minimize drag on the deformed airfoil shape. More recently, Stanford and Ifju [12] used topology optimization to design the layout of a two-material membrane-skeleton structure, which formed the wing of a micro air vehicle. Here they sought to maximize the lift-to-drag ratio using an unconstrained formulation. This example also included aerostructural coupling with a vortex lattice method used to compute the aerodynamic forces.

These examples have successfully demonstrated the usefulness of topology optimization for designing aircraft structures. However, each of these studies has been limited to problems involving two-dimensional design domains, and, with the exception of Maute and Reich [11], they have focused only on the design of the structural topology while keeping all other aspects of the design fixed. As a result, these techniques fail to fully exploit the potential of the method. The approach presented in this paper integrates topology optimization into a full MDO framework in which the aerodynamic shape is also optimized. In this way, the procedure is able to explore the interplay between the structural and aerodynamic response of the design. In order to achieve this, we implement a computational solver for performing coupled aerostructural analysis along with an adjoint solver for performing coupled sensitivity analysis.

In addition to focusing exclusively on the structural design, the above-mentioned studies have an additional drawback in that they limit the design region to predetermined, two-dimensional zones (e.g. the area inside the rib). In an earlier study by Bayandor et al. [13], it was shown that superior designs could be achieved by optimizing the topological layout of the ribs and spars prior to optimizing the internal design of each component. In a procedure similar to that employed by Boeing [4], Bombardier [3] and Airbus [1], they performed topology optimization on the structural layout of an aircraft Krueger flap, and then optimized the thicknesses and lay-up configurations of the composite laminates used in each component. The present study focuses on the first step in the above procedure, (i.e. the conceptual design of the structural layout of a swept wing). We combine the three-dimensional design approach with multidisciplinary analysis and optimization, to optimize the full three-dimensional region inside the wingbox. Therefore, the optimizer is able to distribute material anywhere inside this region with no assumptions being made a priori about the number or placement of ribs and spars. This three-dimensional approach provides increased flexibility and allows for the possibility of unconventional structural configurations. At the same time, this approach entails a much larger number of finite elements, and therefore it necessitates the implementation of an efficient algorithm for solving the coupled aerostructural analysis problem. In the results presented, we use an approximate Newton–Krylov method, which is implemented in parallel.

2. Concurrent aerostructural design optimization

The simulation and evaluation of the performance of aircraft wings is inherently a multiphysics problem. At the minimum, it requires an aerodyanmic solver and a structural analysis model to determine the aerodynamic forces on the wing, as well as a structural model to determine the structural response of the wing to the aerodynamic loads. These two tasks are coupled since the structural deflection of the wing contributes to its effective aerodynamic shape, thus influencing the nature of the aerodynamic forces. Therefore, when performing computational design optimization of a wing, it is important that the aerodynamic and structural analysis modules take this coupling into account. Furthermore, because of this coupling, it is important to optimize the structural design and the aerodynamic shape concurrently so that the optimizer can make use of the interplay between these two closely related aspects of the design [8].

Previous efforts at topology optimization of aeroelastic structures were limited to problems in which the jig shape of the wing's aerodynamic outer surface was fixed. Note that *jig shape* refers to the geometric shape of the wing exterior when no loading or structural deformation is present. Therefore, although several of the previous studies accounted for the elastic deflection of the wing when modeling the aerodynamic loads, none of them sought to optimize the jig shape, which remained "fixed" from an optimization standpoint. This can be seen as a form of *sequential* optimization in which the outer shape of the wing is optimized at an earlier stage of the design process, and the optimized shape is treated as a fixed design feature when optimizing the internal structure of the wing. As shown by Martins et al. [8] and Chittick and Martins [9], this form of sequential optimization leads to suboptimal designs. Therefore, the current study improves upon previous methods by integrating shape optimization into the aerostructural topology optimization algorithm. These results are then compared with sequentially optimized designs in order to better understand and quantify the benefits of the concurrent MDO approach.

In this context the terms "optimal" and "suboptimal designs" refer to *mathematical* optima, which are optimal only with respect to the specific optimization problem as defined in (18). This is not the same as finding the "best possible" design, as it may be possible to improve upon the mathematically optimized designs by introducing additional design variables, objectives, or constraints. The problem definition used in this study was chosen as a way to investigate specific trends related to MDO and to demonstrate the advantages of concurrent optimization when compared with previous approaches.

In order to solve the aerostructural optimization problem, we implement an MDO algorithm that is based on the *multidisciplinary feasible* (MDF) architecture [14]. A diagram of the algorithm architecture is shown in Fig. 1. This approach solves the coupled

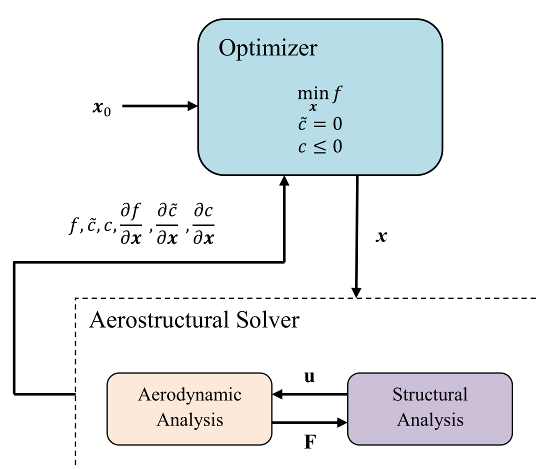

Fig. 1. MDF architecture for a generalized aerostructural problem.