Optimization of Laminated Composite Aircraft Structures

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Introduction

An aircraft structure, like those shown in Figure 1, has some amount of fixed mass that is non-designable. This mass can include passengers, payload, transport weight, fuel, and non-modifiable components, among other things. Along with this fixed mass, there is the structural mass: the wings, tail, fuselage, landing gear, etc. The goal is to reduce the structural mass of the vehicle as much as possible while maintaining the structural integrity of the aircraft. By doing so, the aircraft can achieve better fuel efficiency, utilize less material, and potentially carry greater payload, all of which translates into reduced costs.

When designing composite aircraft structural components, a common goal is to identify the aircraft geometry, as well as the laminate scheme, that will minimize structural mass while satisfying constraints on structural performance (accelerations, buckling factors, displacements, material failure criteria, etc.). It is also desirable to design composite components with manufacturability in mind, where symmetric, balanced laminates are designed with consideration for ply drops and overlaps.

Since the external surface geometry of a given aircraft is typically fixed based on aerodynamic considerations, the composite laminate schemes (number of plies, ply material and orientation, and ply boundary shapes) offer the greatest potential for mass reduction.

There is a complex relationship between the components in aircraft structures and the effect on their performance. This is compounded by the large number of design variables and load cases typical with competing performance goals. These characteristics make it very difficult to design efficient aircraft structures using a manual process. As a result, the design of composite aircraft structural components for maximum weight reduction and optimal performance often requires advanced mathematical processes such as multi-disciplinary design optimization.

(a) Airplane *(b) Unmanned aerial vehicle*

Figure 1. Example of composite aircraft structures.

Aircraft Structural Analysis and Design Models

In this example, the composite structural aircraft components being designed were a fuselage, a tail (Figure 2), and wings (Figure 3).

A manual design process was attempted first. The shape of the tail, wing, and fuselage were fixed during this manual design process, based on aerodynamic design criteria. Nastran was used to perform the finite element analyses used in the design process. The load cases considered took into account such things as flight and landing loads. In all, four load cases were considered for the tail design, two load cases for the wing design, and twenty load cases for the fuselage design. Buckling was considered for all components. The ply boundary shapes and lamination schemes were developed during this manual design process, based largely upon intuition and experience. These quantities were fixed during optimization.

After the manual design process, HEEDS MDO (Hierarchical Evolutionary Engineering Design System – Multi-Disciplinary Optimization) was used to perform a set of automated optimizations to complete the design of the structural components. The optimization efforts focused on varying the number of plies, the orientation of the plies, and the materials used (fabric or uni-directional), such that the mass of the structural components were minimized while Tsai-Wu failure criteria and buckling constraints were met for all load cases.

The optimization studies contained not only a large number of variables, but also mixed types of variables. Both discrete (material properties) and continuous (integer number of plies and ply orientations) variables were present.

To search this complex design space, the SHERPA algorithm was used. SHERPA is a proprietary hybrid and adaptive search strategy available only in HEEDS MDO. During a single parametric optimization study, SHERPA uses the elements of several search methods simultaneously in a unique blended manner. This approach attempts to take advantage of the best attributes of each method. Attributes from a combination of global and local search methods are used, and each participating approach contains internal tuning parameters that are modified automatically during the search according to knowledge gained about the nature of the design space.

This evolving knowledge about the design space also determines when, and to what extent, each approach contributes to the search. In other words, SHERPA efficiently learns about the design space and adapts itself to effectively search many kinds of design spaces, even very complicated ones. SHERPA is a *direct* optimization algorithm, in which all function evaluations are performed using the actual model, as opposed to using an approximate response surface model. SHERPA does *not* require solution gradients to exist. The only parameter the user needs to specify is the number of allowable evaluations.

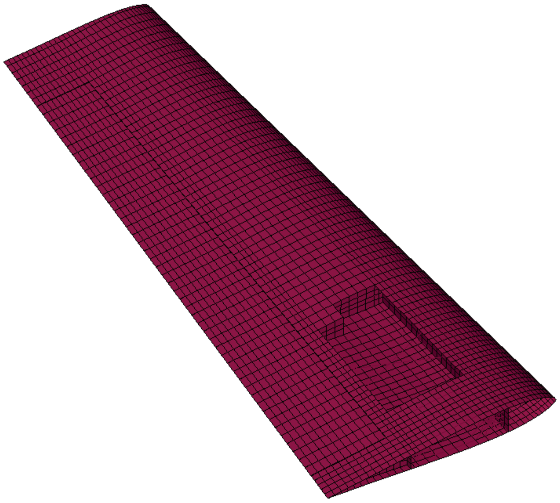

Figure 2. MSC Nastran shell finite element model of the tail components.

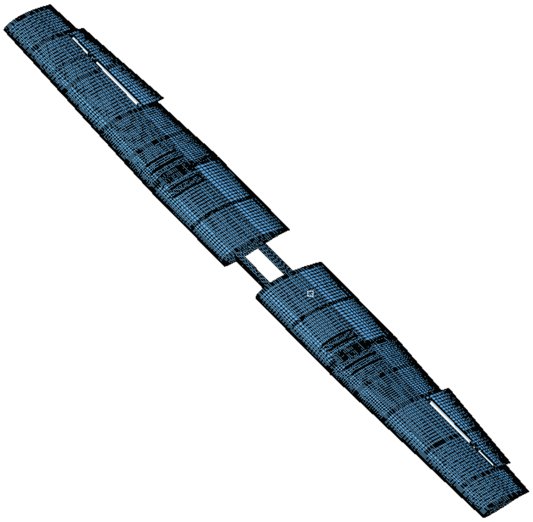

Figure 3. MSC Nastran shell finite element model of the wing component.

Tail Optimization

The tail optimization utilized 12 design variables, including the number of plies for the different sublaminates and the orientation of the different plies. The goal of the optimization was to minimize the mass of the tail. The constraints required that the Tsai-Wu failure indices in the tail not exceed 1.0. In addition, the buckling factors could not be below 1.05. The optimization problem statement for the tail optimization was as follows:

Objective:	Minimize Mass
Such That:	*Tsai-Wu Failure Indices* $\leq$ 1.0 *Buckling Factor* $\geq$ 1.05
By Varying:	*Number of plies in sublaminates* *Orientation of plies*

Using a laminate build-up program developed by Red Cedar Technology, and the lamination scheme developed during the manual design process, HEEDS MDO was able to find a design that reduced the mass in the tail by 3%, while ensuring the constraints were met. Figure 4 shows the design history from HEEDS MDO for the tail optimization.

The baseline design for the tail was not only heavier, but didn't meet the buckling constraints. By reducing the number of plies in certain regions and modifying orientations, the performance of the tail was increased while the mass was decreased.

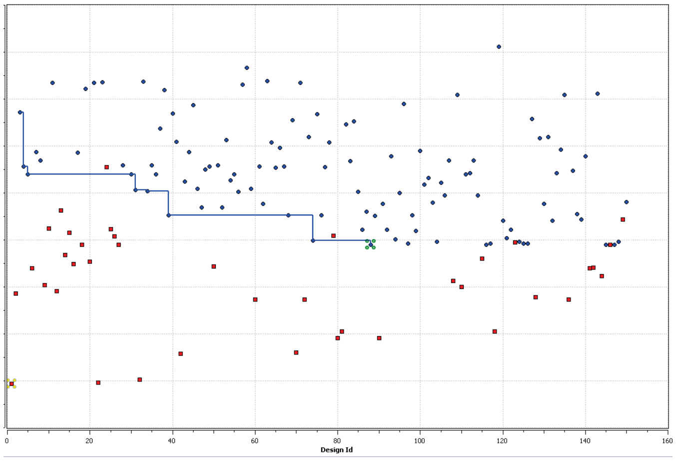

Figure 4. Optimization history plot for the tail optimization performed by HEEDS. The blue designs are feasible designs found during the optimization while the red designs are infeasible designs. The 88th design, highlighted in green, was the optimized design.

Wing Optimization

There were more than 80 design variables for the optimization of the wing, consisting of the number of plies for the different sublaminates, the orientation of the plies, and the material choice for the plies (fiber or uni-directional).

The goal of the optimization was to minimize the mass of the wing. The constraints required that the Tsai-Wu failure indices in the wing not exceed 1.0. In addition, the buckling factors could not be below 1.05. The optimization problem statement for the wing was as follows:

Objective: Minimize Mass

Such That: *Tsai-Wu Failure Indices* $\leq$ 1.0
Buckling Factor $\geq$ 1.05

By Varying: *Number of plies in sublaminates*
Orientation of plies
Fabric or Uni-directional material

By reducing the number of plies in certain regions and increasing the number of plies in other regions, HEEDS MDO was able to optimize the interactions of the many components in the wing, which could not be easily ascertained during the manual design process.

This redistribution of the weight, along with the introduction of uni-directional plies to certain regions of the wing and the modification of ply orientations, allowed HEEDS MDO to find a design that reduced the mass in the wing by 12% while ensuring the constraints were met.

Fuselage Optimization

There were more than 120 design variables for the optimization of the fuselage, consisting of the number of plies for different sublaminates and the orientation of the plies. This optimization considered only fabric material.

The goal of the optimization was to minimize the mass of the fuselage with constraints that the Tsai-Wu failure indices in the fuselage not exceed 1.0 and the buckling factors not fall below 1.05.

The optimization problem statement for the fuselage optimization was as follows:

Objective: Minimize Mass

Such That: *Tsai-Wu Failure Indices* $\leq$ 1.0
Buckling Factor $\geq$ 1.05

By Varying: *Number of plies in sublaminates*
Orientation of plies

By reducing the number of plies in certain regions and increasing the number of plies in other regions, HEEDS MDO was able to optimize the interactions of the many components in the fuselage. This redistribution of weight, along with the modification of ply orientations, allowed HEEDS to find a design that reduced the mass in the fuselage by 9% while ensuring the constraints were met.

With the 20 load cases present in designing the fuselage, over 35% of the designs evaluated during the optimization were found to be infeasible, a testament to the difficult design landscapes typical of these types of composite problems.

Figure 5 shows a constraint violations plot (available in HEEDS POST) that can be used to view which constraints were active for the majority of the designs. This plot provided useful information about the design of the fuselage as the optimization run progressed.

Two of the landing loading conditions proved to be the most difficult to satisfy for the Tsai-Wu failure conditions.

Table 1 summarizes the mass savings for all of the structural components of the aircraft via optimization.

Table 1. Mass savings obtained for the composite aircraft structural components through optimization with HEEDS MDO.

Structural Component	Percentage Mass Savings
Tails	3 %
Wing	12 %
Fuselage	9 %

Conclusions

A new strategy was presented for using HEEDS MDO to optimize composite aircraft structural components. This approach yielded designs that were lighter and higher performing than those found with a manual design process. The systematic approach to the setup and solution ensured that the final design was efficient and conformed to the manufacturability constraints. The result was a lighter aircraft design, with mass savings of 3% in the tail, 12% in the wing and 9% in the fuselage.

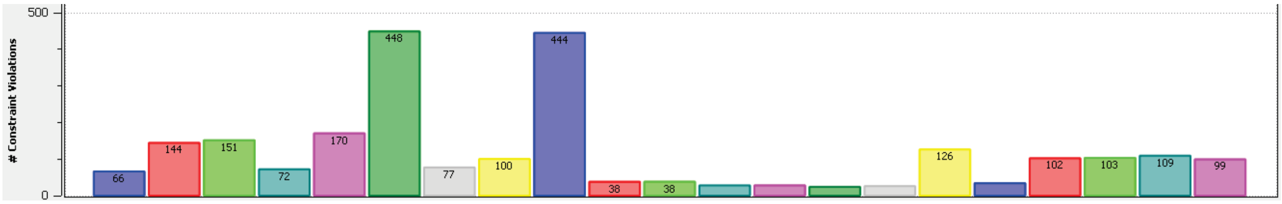

Figure 5. Constraint violations plot for the fuselage optimization performed by HEEDS. Two of the landing load conditions accounted for the most constraint violations in the Tsai-Wu failure criterion during the optimization of the fuselage.