A Two-Step Approach to Multi Spar Composite Vertical Empennage Structure Optimization

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Abstract
A two-step approach for the structural optimization of a multi spar vertical empennage fully constructed with laminated composite materials is presented, whose output is the composite lay-up over the structure with optimum stacking sequence. For the minimization of structural weight only the critical buckling load factor design constraint is imposed and structural analysis is done for critical maneuver load case. In the first step of the structural synthesis a zone modeling strategy is applied over a design model where groups of four adjacent elements have the same composite lay-up and a single thickness design variable. A thickness gradient criterion is applied to regroup adjacent regions. The zone modeling iterations proceed until the convergence to the final set of zones. Once this set of zones is defined over the structure new detailed laminate properties are assigned to the regions and a new final discrete optimization is carried out, now with angle and thickness discrete variables such that the stacking sequence is optimized and the final laminate presents ply continuity along the zones. The structural optimization software GENESIS® is used in both steps. Result show that the strategy is very effective in producing a manufacturable structure.

Keywords: Composite, zone modeling, blending, stacking sequence, vertical empennage.

1. Introduction
Most literature on composite laminates consider the components of a system as autonomous structures, designed as if they were isolated from other parts, not worrying about the fact that the laminates can be part of a bigger structure that must be manufactured entirely.

Designing laminates for multiple components while maintaining good characteristics of manufacturability is quite desirable. There are at least two main issues in the question: a) how to define adequate independent regions of laminates with their own elastic properties? b) how to maintain adequate continuity among laminates?

These issues have gained attention recently and there is enough accumulated experience that currently allows the implementation of several alternatives with this purpose in [1,2]. In [1], where each finite element has a unique property, the concept of automatic zone modeling was launched. It consists on reducing a complex collection of independent properties of finite elements to a smaller number of regions using a similarity criterion to adjacent elements based on a concept somewhat relaxed of elastic property gradient. The same idea is applied with great success to a horizontal stabilizer of a real military aircraft [3].

The design of composite laminated wings with good blending characteristics has gained attention. The discrete nature of the problem of determining the thickness or number of layers in certain directions and the desire to use a small group of directional fibers such as (0°, 45°, -45°, 90°) to facilitate the manufacturing effort, coupled with ease implementation, makes genetic algorithms a good tool for the design of the sequence of lamination, which justifies its extensive use in most studies in recent literature [2]. However the use of genetic algorithms is too much time consuming, because too many FE analysis are necessary to converge.

The concept of key regions in a multi-level formulation is used in [4]. Formulations of constraints on continuity where imposed in [5] in two ways: continuity of material at the global level and continuity of stacking sequence on local levels. In [6] multiple laminates and sub-zones are used to design structures completely continuous. The optimization process of each panel in a first step is to optimize them individually. From the individual optimal solutions begins a second stage based on the minimum number of layers needed for each panel obtained in the first step. The process can be extended to a number of steps until we obtain the desired result.

In this work a two-step methodology is presented to produce optimal solutions such the structure is subdivided in zones by a zone modeling strategy similar to the one presented in [1]. However, here a simpler gradient criterion is used to group adjacent regions, which is based solely on the thickness of the regions. A sequence of optimization cycles with just one thickness variable per zone is carried out until convergence to a final set of zones is achieved. Thereafter, new detailed laminate properties are assigned to the regions and a new final discrete optimization is carried out, now with angle and thickness discrete variables such that the stacking sequence is optimized and the final laminate presents full ply continuity along the zones [8]. The structural optimization software GENESIS® is used in both steps. Result show that the strategy is very effective in producing a manufacturable structure.
2. Optimization Methodology

2.1 Zone Modeling Optimization

In the zone modeling phase a simplified laminate is specified with four lamina directions of $0^\circ$, $45^\circ$, $-45^\circ$, and $90^\circ$. Each zone can be just one finite element or a group of finite elements, for example, in Fig. 1 the initial zones are made of four finite elements. Just one thickness design variable is assigned to each design zone, such that each direction layer has $1/4$ of the total thickness. As suggested in Barker et al. (2002) a reduced number of zones can be created based on the gradient of elastic properties between adjacent zones. Here we use a simpler form of gradient, with respect only to thickness differences, i.e., \( \text{gradient} = t_0 - t_1 \), where \( t_0 \) is the ply-layer thickness of the parent zone and \( t_1 \) is the ply-layer thickness of adjacent zone. Depending on the value adopted for the gradient the thicker parent zone can agglutinate a thinner adjacent zone to itself. Therefore a ply-layer zone propagates from the parent zone agglutinating other thinner zones until the allowable gradient is exceeded. At the end several constant thickness zones of decreasing thicknesses will have been defined over the structure, which can be called the initial set of reduced zones. A second set of reduced zones can be generated and this is the strategy adopted here (in Barker et al. just the first set of zones is modeled). For the definition of the next and following sets of zones a new optimization is carried out and the process of zone modeling is repeated, until convergence of the zones to a final zone distribution is achieved.

![Figure 1- Zone representation](image)

Here the program GENESIS® is employed in such a way that after the optimization of the current set of zones its output file is read and the zone modeling strategy is applied using the gradient allowable such that the finite element model is organized into a new input file with a new set of zones for a new optimization cycle.

2.2 Sizing Optimization (stacking sequence)

The sizing methodology is generic and can be used in any type of software that uses the bulk data property card for composite materials similar to “PCOMP” NASTRAN® bulk card. The laminate property card defines the stacking sequence for a laminate composite as shown in Table 1.

<table>
<thead>
<tr>
<th>PCOMP</th>
<th>PID</th>
<th>Z0</th>
<th>NSM</th>
<th>SB</th>
<th>FT</th>
<th>TREF</th>
<th>GE</th>
<th>LAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>MID_1</td>
<td>T_1</td>
<td>θ_1</td>
<td>SOUT_1</td>
<td>MID_2</td>
<td>T_2</td>
<td>θ_2</td>
<td>SOUT_2</td>
<td></td>
</tr>
<tr>
<td>MID_3</td>
<td>T_3</td>
<td>θ_3</td>
<td>SOUT_3</td>
<td>MID_4</td>
<td>T_4</td>
<td>θ_4</td>
<td>SOUT_4</td>
<td></td>
</tr>
<tr>
<td>……</td>
<td>……</td>
<td>……</td>
<td>……</td>
<td>……</td>
<td>……</td>
<td>……</td>
<td>……</td>
<td>……</td>
</tr>
<tr>
<td>MID_N-1</td>
<td>T_N-1</td>
<td>θ_N-1</td>
<td>SOUT_N-1</td>
<td>MID_N</td>
<td>T_N</td>
<td>θ_N</td>
<td>SOUT_N</td>
<td></td>
</tr>
</tbody>
</table>

The meaning of the PCOMP bulk card fields are as follows:

Table 1. PCOMP Bulk Data
The fields that define the laminate during the optimization are the thickness and angles of each ply. These quantities will be associated to discrete design variables, as is shown in Table 2, where the thickness are now represented by design variables $VT_j$ and the angles by design variables $V\theta_j$. These design variables take their values from lists with discrete values, such as $[0, t, 2t]$ and $[0^\circ, \pm45^\circ, 90^\circ]$. The optimal stacking sequence will be the result of the choice of ply thickness and angle. A ply can be eliminated for practical purposes when its thickness assumes the zero value, which in fact is just a very small number used to avoid error messages in the code. For practical reasons ply angles are limited to the discrete set $0^\circ, 90^\circ, \pm45^\circ$ and the thickness values are integer multiples of the commercially available ply thickness.

The implementation of the strategy was carried out in two steps:

1. Definition of the initial lay-up, preferably after a previous structural analysis, in order to avoid an unnecessary high number of design variables. In our case, symmetric and balanced laminates were imposed. With this configuration the number of variables number is half of the number of plies.
2. Association of design variables $VT_j$ and $V\theta_j$ with PCOMP fields. The Table 2 shows a typical symmetric and balanced composite laminate using optimization variables, where for the LAM field (see Table 1) of the card is changed to SYM.

### Table 2. Balanced and Symmetric PCOMP Bulk Data writing using optimization variables

<table>
<thead>
<tr>
<th>PCOMP</th>
<th>PID</th>
<th>Z0</th>
<th>NSM</th>
<th>SB</th>
<th>FT</th>
<th>TREF</th>
<th>GE</th>
<th>SYM</th>
</tr>
</thead>
<tbody>
<tr>
<td>MID1</td>
<td>VT1</td>
<td>V01</td>
<td>SOUT1</td>
<td>MID1</td>
<td>VT1</td>
<td>-V01</td>
<td>SOUT1</td>
<td></td>
</tr>
<tr>
<td>MID2</td>
<td>VT2</td>
<td>V02</td>
<td>SOUT2</td>
<td>MID2</td>
<td>VT2</td>
<td>-V02</td>
<td>SOUT2</td>
<td></td>
</tr>
<tr>
<td>....</td>
<td>....</td>
<td>....</td>
<td>....</td>
<td>....</td>
<td>....</td>
<td>....</td>
<td>....</td>
<td></td>
</tr>
<tr>
<td>MIDN</td>
<td>VTN</td>
<td>V0N</td>
<td>SOUTN</td>
<td>MIDN</td>
<td>VTN</td>
<td>-V0N</td>
<td>SOUTN</td>
<td></td>
</tr>
</tbody>
</table>

The material properties card PCOMP can be conveniently applied in such a way to preserve the zones defined in zone modeling phase of the optimization task and also to define a construction with full laminate continuity between the zones. In the PCOMP card of Table 2 each line has two layers with the same material identification MID. The layers MID must be assigned to the zones in such a way that the thicker zones have more layers assigned to them than the thinner zones. All of the zones have the layer MID1. The thickest zone must have the highest numbered layer (N index in Table 2). At least one new layer must exist when going from a thinner to the next thicker zone. In fact, the number of layers to allocate for each zone can be estimated from the thickness obtained in first optimization phase, i.e., the zone modeling phase. In fact we can work with some slack by using a number of layers higher than the necessary to produce the thickness obtained in the zone modeling phase.

### 2.2.1 Optimization Strategy

The mathematical optimization problem of mass minimization of a composite material structure under buckling load factor constraint is the following:

**Minimize:**

$$M \{VT, V\theta\}$$  \hspace{1cm} (1)

**Subject to:**

$$\lambda \geq 1$$  \hspace{1cm} (2)
where the discrete thickness and angle variables take values from the following lists:

$$VT_i = [10^{-4}, t, 2t] \quad i = 1, 2, ..., N$$ (3)

$$V\theta_i = [0^\circ, 45^\circ, 90^\circ] \quad i = 1, 2, ..., N$$ (4)

A remark is necessary in that the value of $t$ in the list of Eq.(3) is fixed, so that the variable $VT_i$ must be taken from one of the three integer values in the list. It was found that these three discrete values are sufficient for the purpose of optimization. The $10^{-4}$ thickness is used to represent a thickness that should be eliminated from the PCOMP card, but can not because it would cause an error message in the finite element code. In fact, this option of near zero value for the thickness variable is the key to allow staking sequence optimization.

2.3 Composite Laminate Structure Optimization Flowchart

To clarify the approach proposed to perform the two-step optimization of the vertical empennage, a flowchart is shown in Fig. 6. It is important to mention that optimization finds the best zone arrangement using continuous design variables, while the sizing design uses integer design variables to find the best laminate staking sequence. In both cases the optimization is constrained for buckling load factor and the objective is weight minimization.

3. Multi Spar Composite Empennage Description

The multi spar structure has been historically used since it is lighter when compared to classical constructions. The multi-spar construction excludes the necessity of skin stiffeners and ribs to resist compression buckling loads. An example of this application is the Embraer Phenon® airplane.

Geometric Data Information for vertical empennage is detailed in Table 5.

It was selected a gust lateral critical load symmetric in both sides, with maximum vertical load factor (Nz), considering MTOW for a generic aircraft and center of gravity in back asymmetry position as critical load case. Table 6 has the graphite-epoxy ply mechanical properties used for the empennage construction.

4. Multi Spar Composite Results

4.1 Zone modeling

The zone modeling iterations, for a thickness gradient of 0.25mm, took five optimization cycles to converge from a configuration with 90 zones to a final configuration with 10 zones, as is shown in Tab. 7. After each cycle the finite element model was reorganized as a result of evaluation of thickness gradients and the application of the zone modeling strategy. Figure 6 shows the zones arrangement after each zone modeling optimization cycle.

In the zone modeling phase it is expected that a higher number of zones would lead to a lower structural weight. However, this did not happen since the optimal solutions with fewer zones showed decreasing weights, as can be observed in Fig. 8. A possible reason for this behavior is that GENESIS® "Bigdot" algorithm is not the ideal tool to handle discrete variables, because discrete solutions are obtained by rounding from the continuous solutions [7]. In this case, the higher the number of variables the worse is the discrete solution. Figure 8 shows the jumps corresponding to the rounding of continuous do discrete solutions, which in fact are smaller in the later cycles of
zone modeling optimization. This argument would explain the better results obtained when using fewer zones. After the 5º cycle, the finite element model was reorganized for the last time and became the input file to start the stacking sequence optimization. Figure 5 shows property numbers adopted in the runs which are also present in the results of Tab. 8.

![Composite Laminate Optimization Flowchart](image)

**Figure 4. Composite Laminate Optimization Flowchart**

**Table 5. Zone Modeling Results**

<table>
<thead>
<tr>
<th>Optimization Cycle</th>
<th>Zones</th>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1º</td>
<td>90</td>
<td>59.56</td>
</tr>
<tr>
<td>2º</td>
<td>53</td>
<td>58.07</td>
</tr>
<tr>
<td>3º</td>
<td>20</td>
<td>57.45</td>
</tr>
<tr>
<td>4º</td>
<td>16</td>
<td>54.07</td>
</tr>
<tr>
<td>5º</td>
<td>12</td>
<td>54.65</td>
</tr>
</tbody>
</table>
Figure 5. Vertical Empennage Composite Zones

Initial set – 90 zones

1st cycle – 53 zones

2nd cycle – 21 zones

3rd cycle – 16 zones

4th cycle – 12 zones

5th cycle – 10 zones

Figure 6. Zone modeling results
4.2 Sizing optimization
The final thickness results for vertical empennage structure are shown in Fig. 7. Moreover, Genesis output history graph is in Fig. 8. The final lay-up presented in Tab. 8 has full ply continuity along the five skin zones as anticipated in Section 2.2.

![Figure 7. Final thickness results](image)

![Figure 8: Genesis optimization cycles history](image)

Table 8: Stacking Sequence Results

<table>
<thead>
<tr>
<th>Zone</th>
<th>Thickness [mm]</th>
<th>Stacking Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000</td>
<td>2.16</td>
<td>[90₂, ±45]</td>
</tr>
<tr>
<td>20000</td>
<td>2.16</td>
<td>[0₂]</td>
</tr>
<tr>
<td>30000</td>
<td>2.16</td>
<td>[90₂, ±45, 0₂]</td>
</tr>
<tr>
<td>40000</td>
<td>2.16</td>
<td>[0₂]</td>
</tr>
<tr>
<td>50000</td>
<td>2.16</td>
<td>[90₂, ±45₂]</td>
</tr>
<tr>
<td>100000</td>
<td>1.44</td>
<td>[±45₂]</td>
</tr>
<tr>
<td>100001</td>
<td>2.16</td>
<td>[±45₂, 0₂]</td>
</tr>
<tr>
<td>100002</td>
<td>2.88</td>
<td>[±45₂, 0₂, 90₂]</td>
</tr>
<tr>
<td>100003</td>
<td>3.60</td>
<td>[±45₂, 0₂, 90₂]</td>
</tr>
<tr>
<td>100004</td>
<td>4.32</td>
<td>[±45₂, 0₂, 90₂]</td>
</tr>
</tbody>
</table>
4. Conclusion
A multi spar composite laminate empennage structure was optimized using the proposed two-step approach. The approach was very effective on zone modeling as well as on finding the optimal lay-up. The zone modeling was done using five optimization runs starting from 90 zones and converging to 10 zones. The stacking sequence optimization proposed was very effective since it allowed direct action on the PCOMP card, with no need of complicated enhancements. The proposed two step approach is planned to be utilized in other applications and compared to methods of the same kind.

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