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Optimal design of blended composite laminate structures using ply drop sequence

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ABSTRACT

In this paper, the concept of ply drop sequence (PDS) is introduced for designing of composite laminate structures with multiple regions. The PDS describes the order of ply-drops from the thickest guide laminate to a series of thinner ones, and further ensures laminate continuity across the entire structure. Comparing with deleting a contiguous innermost/outermost plies in the classical guide-based blending, using PDS is more flexibly of dropping plies between adjacent regions. A fully blended design is represented by a stacking sequence of the guide, a PDS and a thickness distribution over the whole regions of the structure. A genetic algorithm (GA) with special operators and codification is adopted for the PDS-based blending optimization, which guarantees the design is completely blended within the GA iterations. The proposed method is applied to an 18-panel horseshoe benchmark problem to demonstrate its flexibility and potentiality.

1. Introduction

Due to the high specific strength and stiffness, fiber-reinforced composites are increasingly used in automotive, aerospace and marine structures. An advantage of using fiber-reinforced composites is that the materials can be tailored to specific requirements of certain applications [1], through the variation of thickness, fiber orientation as well as stacking sequence. However, the great elastic tailoring capabilities bring not only gains in efficiency, but also a large set of design variables, which makes the structural design much more challenging than the one involving conventional materials. Design optimization offers a useful tool to adjust these variables to achieve the maximum material performance.

Design of composite laminate is a discrete optimization problem, since in practice the ply thickness is usually fixed and fiber orientation angles are often restricted to a discrete set to meet manufacturing constraints. The discrete nature of the composite optimization problem makes genetic algorithms (GAs) stand out in comparison with the other optimization techniques, especially the gradient-based methods. Due to its simple coding, escaping of gradient evaluations, and flexibility for a large variety of problems, GA has become the most popular method for stacking sequence optimization of composite laminates [2,3]. A further discussion about stacking sequence optimization of composite structures can be found in a literature review by Ghiasi et al. [2].

For large structures, e.g. a wing, the design process is composed of design optimization of local regions, or panels. In the case of composite structures, the local details of a panel are mainly associated with the stacking sequence of the laminate. The simplest and straightforward way to tailor such problems is optimizing the panels separately. However, this will inevitably lead to incompatibility in stacking sequence of adjacent panels from manufacturability and structural integrity points of view.

In order to avoid laminate discontinuity, Kristinsdottir et al. [4] have introduced a methodology termed *blending*. In their work, each ply emanates from the key region, or the thickest region, and may continuously cover any number of adjacent regions. Meanwhile, each ply is allowed to be discontinued, but once dropped, it is not allowed to be added back into the structure. This way of consistently dropping plies from the most loaded region is named the *greater-than-or-equal-to blending* rule. This method is not suitable for the structures that have several disconnected key regions.

In the works of Soremekun et al. [5] and Liu et al. [6], a *shared layer blending approach,* which is a two-step optimization procedure, has been developed to design blended laminates. The first step is individually optimizing the stacking sequence of each panel for minimum weight without blending constraint. The second step is to perform the blending optimization, based on the minimum number of plies required by each panel in step

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one. The drawback of this method is that the initial objective function step is not taken into account in the second step [7].

The concept of *guide-based blending* is introduced by Adams et al. [8]. In this approach, a template stacking sequence, referred to as a *guide*, is used to ensure the blending between panels. From the guide, a certain number of contiguous plies either at the top or at the bottom are kept to represent a particular panel. The advantage of this approach is that it produces blended designs without any blending constraint. However, the assumption restricts the optimization problem to only a small region of the design space [9].

A more recent approach to blending problem is a *stacking sequence table (SST) based* design methodology [10]. In this approach, plies are added one by one from the thinner laminate to the thicker one which is described by SST. A blended design is represented by a SST combined with a thickness distribution over the regions of the structure. Compared to the classical guide-based blending, this methodology provides more freedom to tailor the laminates.

In the present work, the classical guide-based blending is enhanced to pursuit more general blended designs similar to SST-based blending. The paper is organized as follows: the concept of ply drop sequence and the construction of a laminate using PDS are introduced in Section 2; a customized GA for the new approach is presented in Section 3; finally, in Section 4, the GA framework is implemented on a 18-panel benchmark problem, and the results are compared with the optimal designs in relative literatures.

2. Ply drop sequence

In blending design, between two adjacent regions, the plies composing the thinner region should be a subset of the ones of the thicker region. In general, the blended designs can be found mainly in two ways. One way is to exclude the infeasible designs through blending constraints, such as in Ref. [11]. A penalty function, based on Levenshtein edit distance [12] between the stacking sequences of two adjacent regions, is used in optimization process. The other way is to use blending rules which describe the ply drop-offs between two adjacent laminates to ensure continuity, such as Refs. [4,8,10,13]. A common feature of these blending rules is the guide stacking sequence. Each laminate is produced by cutting or dropping certain plies from the guide. This assumption reduces the difficulty of blending problems and eliminates the need for continuity constraints, although in turn leads to less flexible compared to the first way.

Up to now, several blending rules have been defined. Among them, the classical guide-based blending rule is the simplest and the most efficient, since the drop-off orders are fixed in advance: in the case of inner/outer blending, a contiguous innermost/outermost plies are deleted from the guide design. Once a region's thickness is known, the stacking sequence of this region can be determined and read from the guide. However, this blending algorithm is relatively strict and hence narrows the search space significantly. In order to search more efficiently in the design space, while maintaining the simplicity of classical guide-based blending, the concept of ply drop sequence (PDS) is introduced and described in the following paragraphs.

Suppose a guide has $n_{\max}$ plies and each ply is associated with a number representing its location through the thickness direction. For symmetrical laminate, plies from the outermost to the innermost are numbered from 1 to $n_{\max}$, respectively. PDS is a permutation of these $n_{\max}$ integers, and allows to define any ply drop-offs. The new parameterization of ply drop-off rule defines the ply order following which the plies will be sequentially deleted. In other words, plies will be deleted from the guide sequence according to the order of their values in the PDS. The progress of creating laminates using the concept of PDS is shown in Fig. 1.

Suppose there is a PDS of (2 4 3 6 1 5) and a guiding sequence of (45 -30 0 30 -45 90), as shown in Fig. 1. For a laminate with 4 plies, the plies corresponding to the very two beginning of PDS, ply number 2 and 4, should be deleted from the guide. Since the plies of the guide are numbered as (1 2 3 4 5 6), the ply number 2 and 4 are associated with ply -30 and ply 30 respectively. By removing these two plies, the consequent sequence of the laminate becomes (45 0 -45 90). Then, consider a case where a structure with three regions, or three panels. Ply numbers of panel A, panel B and panel C are set to 3, 4 and 2, respectively. According to the definition of PDS, the corresponding stacking sequences of these three panels are obtained, and are shown in Fig. 1. Therefore, for a given guide and a PDS, the laminates associated with each region can be determined based on the distribution of numbers of plies over regions of a structure. Furthermore, being an extension of classical guide-based blending approach, the stacking sequence of each region can be obtained simply by reading from the guide rather than from the drop off table [13] or the SST [10] which lists all the possible stacking sequences in a table.

As discussed above, any ply could be deleted when laminate becomes thinner, which enlarges the search space and prevents dropping excessive number of plies between two continuous plies. Obviously, classical guide-based blending is a special case of the PDS-based blending. When PDS is fixed to $(1\ 2\ 3, \ldots n_{\max})$ or $(n_{\max}\ n_{\max}-1\ n_{\max}-2, \ldots 1)$, the PDS-based blending becomes inner blending or outer blending. In addition, it is worth mentioning that PDS does not change the stacking sequence of the guide, which means that a region whose thickness is identical to the guide, has the same stacking sequence as the guide no matter what the PDS is.

3. Genetic algorithms for composite laminate structure optimization

GA is a stochastic search technique imitating the processes of natural selection to find approximate solutions of optimization

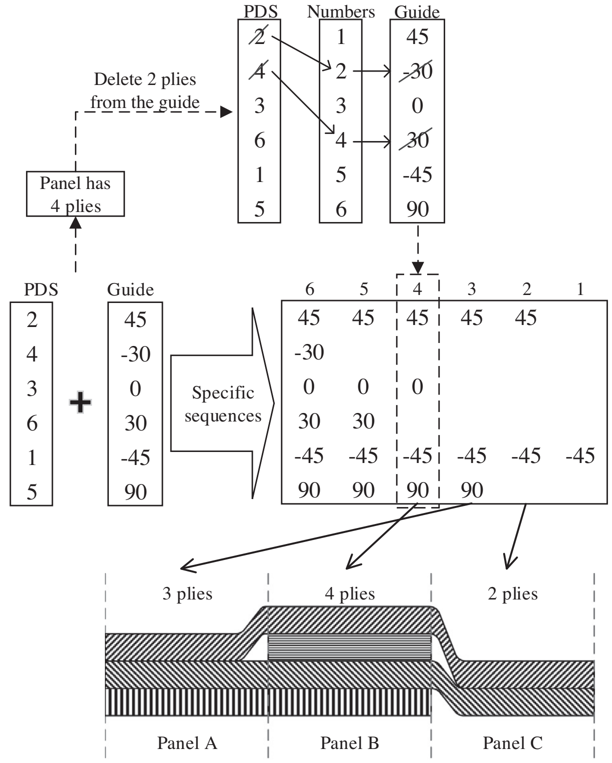

Fig. 1. Illustration of drop-off rule defined by ply drop sequence.