Composite Structures 185 (2018) 132–147

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Multi-objective multi-laminate design and optimization of a Carbon Fibre Composite wing torsion box using evolutionary algorithm

Sachin Shrivastava[a], P.M. Mohite[a,*], Tarun Yadav[b], Appasaheb Malagaudanavar[b]

[a] Department of Aerospace Engineering, Indian Institute of Technology Kanpur, UP 208016, India
[b] AURDC, Hindustan Aeronautics Limited, Nasik, MH 422207, India

ARTICLE INFO

Keywords:
Genetic algorithms
Wing torsion box
Multi-objective optimization
Carbon Fibre Composites
Smart tailoring
Python-scripting

ABSTRACT

The present study aims to minimize the weight of multi-laminate aerospace structures by a classical Genetic Algorithm (GA) interfaced with a CAE solver. The structural weight minimization is a multi-objective optimization problem subjected to fulfilling of strength and stiffness design requirements as well. The desired fitness function connects the multi-objective design requirements to form a single-objective function by using carefully chosen scaling factors and a weight vector to get a near optimal solution. The scaling factors normalize and the weight vector prioritizes the objective functions. The weight vector selection was based on a posteriori articulation, after obtaining a series of Pareto fronts by 3D hull plot of strength, stiffness and assembly weight data points. During the optimization, the algorithm does an intelligent laminate selection based on static strength and alters the ply orientations and thickness of laminae for faster convergence. The study further brings out the influence of mutation percentage on convergence. The optimization procedure on a transport aircraft wing torsion box has showed 29% weight reduction compared to an initial quasi-isotropic laminated structure and 54% with respect to the metallic structure.

1. Introduction

The aerospace structures like wing, fuselage, control surfaces, etc. are multi-laminated complex structural assemblies. The weight optimization of such structures is quite complex task as the design of such structures has to qualify for multiple design criteria. Thus, it is a multi-objective design optimization problem. Moreover, the estimation of design-values of different criteria for such structural problems by closed form solutions is not available. Therefore, the designer has to obtain approximate solutions. The finite element (FE) approximations using softwares like ABAQUS, NASTRAN, etc. are very popular due to their ease and therefore, widely used by designers. To reach optimal solution in multi-objective optimization problem (MOOP), multiple solutions by CAE solver are required in an unguided search environment, which may be highly time taking and inefficient. On the contrast, multi-objective optimization of mathematical problems using GA is well established. Now-a-days along with high speed computational facilities and structured FE meshes, numerical solutions have brought down computational time drastically. Therefore, in a step forward, if the power of evolutionary algorithms is coupled with CAE softwares, then smart tailoring of laminated aerospace structural assemblies can be accomplished. The resulting structural assemblies will be highly optimized lightweight in compliance with structural design requirements. However, as these design requirements are multi-objective in nature, it is difficult to establish trade-off to have an optimal solution. Moreover, in multi-laminated structures the strength and stiffness of assembled/co-cured structure are interdependent, hence, it is required to address such problems on a global basis. The Carbon Fibre Composites (CFC) lamina is highly anisotropic in strength and stiffness, which, in general, is used to form such tailored laminated structures.

In the present work, GA based optimization algorithm has been developed to optimize multi-objective multi-laminate wing structure, which can be applied to design other primary and secondary aircraft structures as well. The GA optimization idea has been well utilized by the authors for small single objective optimization problem of a control surface, where a laminated control surface was optimized for first ply failure index (*FI*) and achieved a weight benefit [1]. However, the real life problems are multi-objective in nature and one such problem for optimal design of wing structure for achieving minimum weight is addressed here. Deb [2] suggested mathematical expression for handling of MOOP, where a suitable single-objective function Z can be defined as a combination of several single objective functions f_i along with respective relative importance factors (weight factors) w_i as,

$$Maximize/Minimize\ Z = w_1 f_1 + w_2 f_2 + w_3 f_3 + \ldots + w_i f_i \quad (1)$$

* Corresponding author.
E-mail address: mohite@iitk.ac.in (P.M. Mohite).

https://doi.org/10.1016/j.compstruct.2017.10.041
Received 30 May 2017; Received in revised form 3 September 2017; Accepted 12 October 2017
0263-8223/

The solution to MOOP is obtained as Pareto optimal front of non-dominated solutions. However, deviating from Pareto front is trading off [3], where the decision maker imposes the preferences and classifies the objectivity of the problem which is governed by the choice of w_i.

The majority of researchers working on GA based design and optimization of laminate stacking sequence have attempted single objective laminate optimization, under different kind of loads and failure criteria [4–7]. However, researchers [8–10] have attempted multi-objective optimization of hybrid laminated plate structures along with FE solution to evaluate the fitness function. In aerospace domain, weight optimization along with deflection and fundamental frequency of laminated plate structures has been discussed in [11,12], respectively. Kim et al. [13] attempted multi-objective and multi-disciplinary design optimization of a supersonic fighter wing. Their study was based only on limited sets of design variables under aerodynamic and structural requirements. On similar lines, direct multi-search technique was used in [14] to get Pareto optimal of non-dominated set which is free of derivatives similar to GA. Gillet et al. [15] studied single and MOOP of composite structures for glass/epoxy UD and glass/epoxy fabric composite along with fibre orientations for a laminated plate under different loads and boundary conditions. They emphasised on ply orientation to be an important parameter during optimization. Hybrid laminated plate optimization was attempted by Kalantri [9] using NSGA II [16].

Blasques et al. [17] discussed MOOP for beams with rectangular, elliptical and box cross-sections. They did weight optimization along with eigenvalue of the structure by change in fibre angle in beam section [17]. This technique brought in nearly 800 fibre orientations as design variables for a beam problem with a 10 layered laminate. The implementation of this technique to multi-laminate optimization will result in a huge problem, which is practically impossible to handle. Although, there are many attempts in GA optimization using FE tools, but studies are primarily limited to plate and shell structures only. The GA based multi-objective optimization has been attempted in other engineering fields also by [18,19] for laminated structures. Apart from GA, ant-colony optimization [20] and artificial neural network [21,22] techniques are also available for optimizing single objective laminated plate structures.

In the present work, authors have attempted application of GA optimization for large aerospace structures like wing and fuselage, which is less explored for multi-objective optimization on assembly basis. This is done by demonstrating it over a transport aircraft wing torsion box (WTB) design. The implementation of multi-objective multi-laminate optimization for large complex structural assemblies like aircraft wing/fuselage has a lot of scope for weight reduction for future aircraft structures. The present industrial practice for design of stacking sequence uses pseudo-optimization, in which specific sets/combination of ply orientation are used to design the structure. The pseudo-optimal design sets are based on past aircraft design experiences, rather than domain search for optimal solution.

The formation of strings for GA based optimization using industrially preferred choice of fibre angles and solving it for failure criterion viz. Tsai-Wu first ply failure index (FI) (strength criterion) and wing tip deflection (stiffness criterion) D, is attempted in the present work. Such multi-objective multi-laminate problems have large number of design variables which are brought to a common platform. To start with optimization procedure, the initial metallic model was converted to an equivalent quasi-isotropic laminated structure after performing equivalent stiffness calculations having equal oriented fibres at 45°. The quasi-isotropic laminated FE model was a starting model, which is submitted to GA optimizer. The GA optimizer strings were defined to contain information about ply orientation and existence of a ply in terms of thickness. To delete a ply from the laminate, the thickness variable is assigned a dummy (near zero) thickness value during optimization after evaluation of laminate by analytical experiments. The orientation and thickness of laminates of initial sized model were

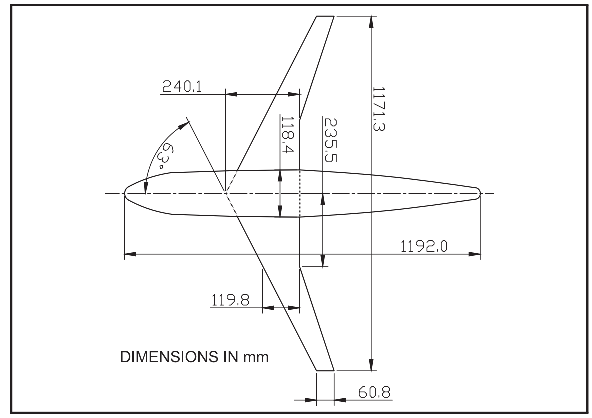

Fig. 1. DLR F6 wing/body planform.

defined in ABAQUS/CAE v6.11 Laminate-Modeler (LM). The LM was externally governed by MATLAB R2014a by a python-script and updated laminates are submitted for FE analysis for the estimation of design parameters to evaluate fitness function of the optimizer. The fitness function defined for GA optimizer was a weighted combination of structural weight, Tsai-Wu FI and wing tip deflection D after normalization.

Apart from the scaling, weight vector w_i was a part of objective function to prioritize the importance of the constraints during optimization. The weights w_i were essentially the fractional numbers such that $\sum_{i=1}^{N} w_i = 1$, where N is the number of objective functions in the final multi-objective function. During optimization the laminate with maximum FI (MFI) is identified at the end of each sub-loop, which guides the solution to optimize the identified laminate in its next iteration.

In the following sections, the basis for metallic wing torsion box design and its subsequent conversion into a quasi-isotropic laminated composite structure followed by the above mentioned optimization have been presented in details.

2. Design of WTB

The DLR-F6 geometry [23] given in Fig. 1 was selected to demonstrate the present optimization procedure. The selected geometry was a scaled version of typical transport aircraft DC-9. The DLR-F6 geometry details are available from AIAA Drag Prediction Workshop (DPW-III) [23,24]. The lift distribution acting on wing geometry was estimated through CFD simulations in ANSYS FLUENT 14.5 after a grid convergence study using ICEM-CFD software [25]. The pressure distributions obtained from the CFD simulations are applied as chordwise segmental pressure load over the wing geometry. The performance parameters of DC-9 aircraft by Endres and Douglous [26] are given in Table 1. The maximum take-off weight of 54.9 tons (including a design factor) was considered as a design load for the present study. The initial sizing [27] for WTB was done considering high strength aluminium alloy of aircraft grade having breaking stress $(\sigma_b) = 410\,MPa$, (yield stress)$\sigma_s = 294\,MPa$, and $E = 69\,GPa$ for maximum take-off weight of the vehicle and maximum D restricted to 10% of wing span [28] at design load. The details of initial sizing can be seen in [27].

Table 1
Basic data of DC-9 aircraft [26].

Length	40.72 m
Span	28.47 m
Wing semi-span	9.7 m
Width of Torsion Box	1.4 m
Height	8.53 m
Wing Area	92.97 m^2
Max take-off weight	54,900 kg