AEROELASTIC TAILORING OF COMPOSITE LIFTING SURFACES BASED ON HIGH-FIDELITY MODELS

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ABSTRACT

Introduction

Aeroelastic studies are crucial in all the industrial applications where air loads are generated, such as buildings, bridges, race cars, airplanes and helicopters. The effects of the interaction among dynamics, elasticity and aerodynamics range from the simple passenger discomfort to even catastrophic failures of the structure, caused by aerodynamic forces that overpower the restoring ones (i.e. stability problems), passing through fatigue related issues. Moreover, aeroelastic phenomena may alter the aircraft response in flight and therefore the control effectiveness has to be carefully investigated [1]. Recently, they became one of the key design drivers due to the increased flexibility of modern structures, which are most commonly made by composite materials. Thus, accurate models must be adopted to properly predict the aeroelastic behaviour of these structures, to avoid safety problems and limit performance related issues. To enhance the aero-structural performance of composite structures, engineers can use the directional stiffness feature of composite materials and properly tailor the mechanical properties of the laminate according to the desired objectives by optimizing the ply lamination angles, hence the name *aeroelastic tailoring*.

Methodology

The present work seeks to perform single and multi-objective optimizations of composite wings, firstly modeled as thin plates, by means of a high order aeroelastic model based on the Carrera Unified Formulation (CUF) [2] and the Doublet Lattice Method (DLM) [3]. Firstly, such model is validated for both the 1D (beam) and the 2D (plate) formulations and the numerical results obtained are compared with the ones present in literature [4]. 2D CUF models are then used to aeroelastically tailor composite wings which are firstly approximated as rectangular, un-swept, symmetric six-layer flat plates, according to the thin-airfoil theory. The optimization to maximize the flutter speed, V_F, of such wings is addressed first, by both selectively neglecting and considering the divergence phenomenon. Simulations are performed for a number of independent lamination angles ranging from one to three and surrogate models are utilized in the latter case. Consequently, multi-objective optimizations are presented for both un-swept and swept plates, aiming to maximize the flutter speed while minimizing the wing mass; the genetic algorithm is adopted in these cases [5]. Finally, multi-objective optimizations of a refined wing-box configuration are illustrated, in order to have a much more realistic representation of an actual flexible wing compared to the afore-mentioned plate models, paving the path for practical applications.

More specifically, the core of the methodology adopted consists in the implementation of an algorithm to automatically obtain the maximum achievable speed of the analysed geometry, which is set by the flutter or the divergence phenomenon, once the ply angles are given as input. Hereafter, the minimum between these two velocities is referred to as *critical speed*, V_C. The main steps of the above-mentioned code can be summarized as illustrated in Fig. 1. Firstly, the lamination angles of the structure are set and the modal analysis by means of the CUF-based Finite Element (FE) code is run. The output file is subsequently read by NASTRAN™ to perform the aeroelastic analysis; the damping and the frequency of each mode per each velocity given as input can be obtained by properly postprocessing the *.f06* file: the flutter condition is detected using a linear interpolation of the velocities at which the damping of a mode passes from negative to positive values and the corresponding frequency is positive. A final check is selectively performed to verify whether the flutter speed is larger than the divergence one or not: in the latter case, the critical speed of the wing is set by the divergence velocity.

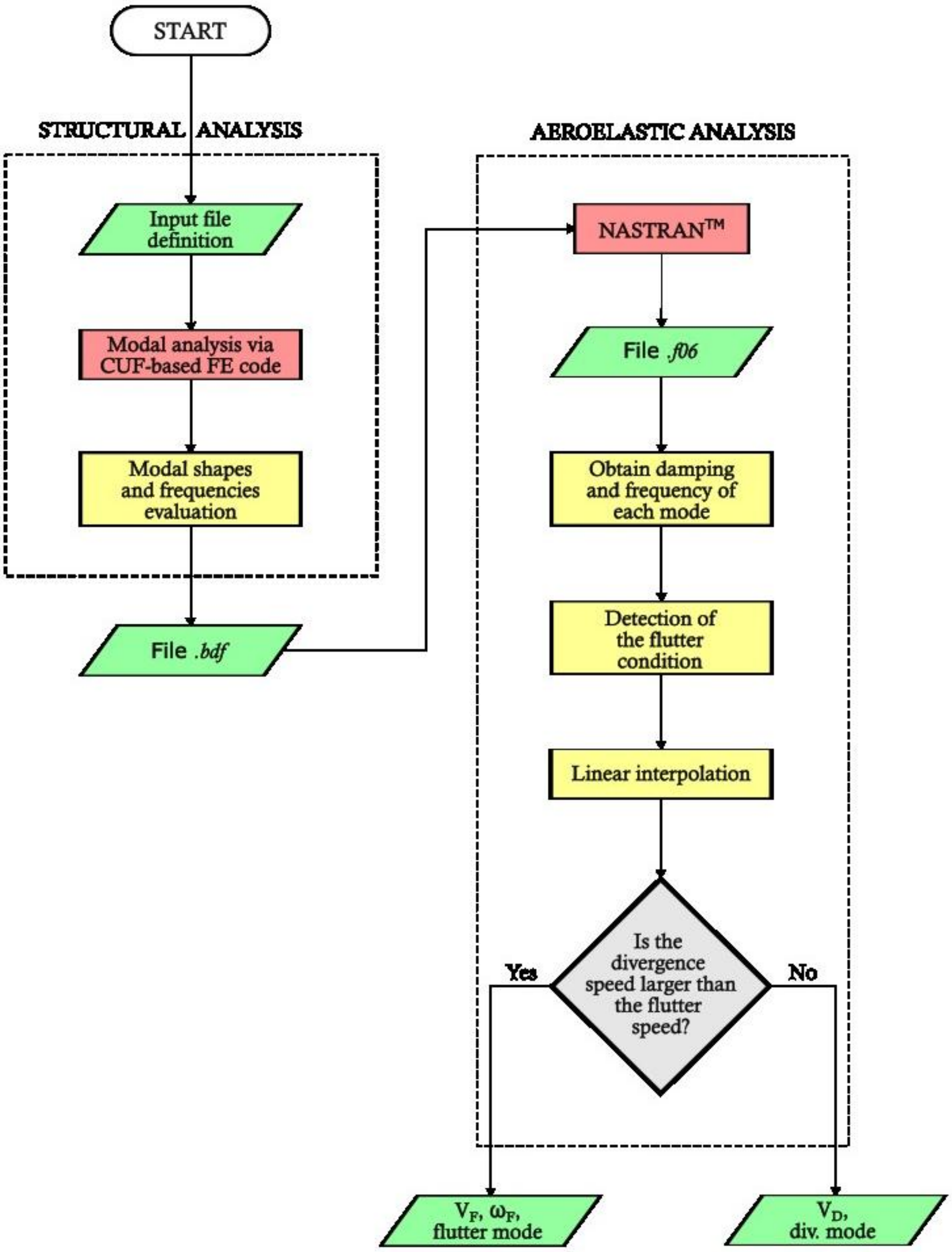

Figure 1. Flowchart of the optimization procedure.

Consequently, the afore-mentioned multi-objective plate optimization problem, for instance, can be formally written as reported in Tab. 1, where V_C is the critical speed, m is the wing mass, α, β, γ are the lamination angles from the most external to the most internal layer, respectively, and t is the plate thickness, which is set to vary between a minimum (t_{min}) and a maximum value (t_{max}).

Table 1. Multi-objective optimization problem formulation.

Objective functions	V_C, m
Design space	$-90° \leq \alpha \leq 90°$ $-90° \leq \beta \leq 90°$ $-90° \leq \gamma \leq 90°$ $t_{min} \leq t \leq t_{max}$
Constraints	6 layers with equal thickness, symmetric plate

Results and conclusions

Firstly, the case with only one design variable, i.e. only one independent lamination angle, is investigated and, in particular, a stacking sequence equal to $[+\theta, -\theta, +\theta]_S$ is arbitrarily chosen; the resulting critical speed as a function of the ply angle is then plotted. Consequently, several insights are presented, in order to investigate the effect of the plate thickness on the difference between the various structural theories adopted, the discontinuous behaviour of the flutter speed with respect to the design variables and the divergence plateau behaviour observed for negative lamination angles. Consequently, the case with two independent design variables is treated and a stacking sequence of $[+\alpha, +\beta, -\alpha]_S$ is selected. The response surfaces that show the dependence of the critical speed on the ply angles are then illustrated. By comparing the optima obtained for the cases of one and two independent design variables, it is possible to observe that they are basically equivalent to each other, while differing only from the most internal lamination angle point of view. Therefore, a study is carried on to analyse the effect of each layer on the critical speed, changing one lamination angle per time while keeping the other two constants; the results are shown in Fig. 2. By observing the plot, it is possible to state that the ply angle of the external layers is the most important one because it makes the critical speed to change significantly. Afterwards, single and multi-objective optimizations, to maximize the critical speed while minimizing the wing mass, are presented for the case of three independent design variables. Surrogate models and Genetic Algorithms are utilized, respectively. Finally, the aeroelastic tailoring of the wing box configuration is treated and, in particular, the similarities/differences with respect to the plate model are highlighted, paving the path for practical applications. From this work, the following two design rules can be drawn for the aeroelastic tailoring of a composite plate:

- if a limited computational power is available, focus on the tailoring of the most external layers, because they are the ones that contribute more significantly to the wing critical speed;
- select a sufficiently accurate structural theory in order to be able to properly detect the shear effects in the internal layers.

To conclude, future works should focus on the usage of such a high-order aeroelastic formulation to analyse wings made by Variable Angle Tow (VAT) composites, with the aim of further improving the structure presented so far, to adopt a more complete aeroelastic framework, including as constraints, for instance, the maximum stress and strain that the model can sustain, and to analyse the effects of the manufacturing defects on the flutter and divergence speeds.

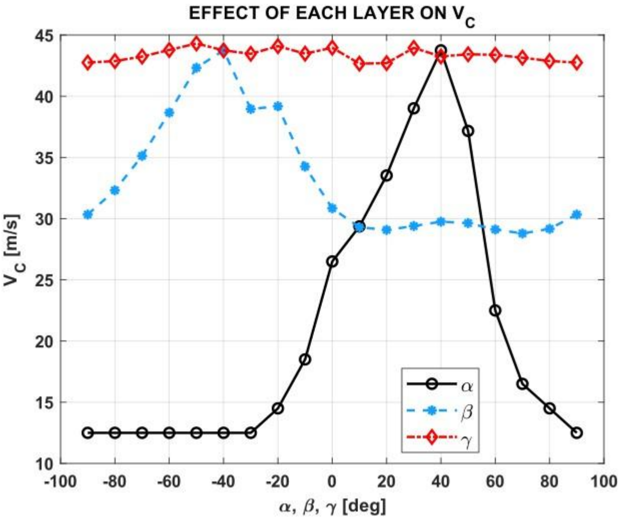

Figure 2. Effect of each layer on the critical speed.

Acknowledgements

This work is the result of a collaboration between the University of Bologna and the Polytechnic of Turin. The authors warmly thank Prof. Sara Bagassi (University of Bologna), Prof. Alfonso Pagani and Prof. Marco Petrolo (Polytechnic of Turin) for their helpful efforts in helping them in the research activity related to this project.

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