CSMA 2022
15ème Colloque National en Calcul des Structures
16-20 Mai 2022, Presqu'île de Giens (Var)

Aeroelastic optimisation of composite structures in aeronautics

M. Sharifi[1], A. Vincenti[2], J-C. Chassaing[1]

Sorbonne Université, CNRS, Institut Jean Le Rond d'Alembert, UMR 7190, F-75005 Paris, France
E-mail: mahshid.sharifi@sorbonne-universite.fr,
angela.vincenti@sorbonne-universite.fr,
jean-camille.chassaing@sorbonne-universite.fr

Résumé — The main purpose of this work is the aeroelastic optimisation of composite laminates. Composite laminates have become a subject of interest in the past decades due to their high strength to weight ratio. These materials have been widely used in the aeronautics and consequently in aeroelastic tailoring which consists on the optimisation of the composite laminates in order to avoid any kind of aeroelastic instabilities. The Optimisation can be conducted both in a deterministic and a stochastic framework. In this study, both aspects have been modelled and investigated.
Mots clés — Composite laminates, Aeroelasticity, Optimisation.

1 Introduction

Aeroelasticity is a domain where the interaction between the aerodynamic and elastic forces is studied. These interactions give place to instabilities which can cause the fatigue or complete failure of the structure. The static aeroelastic instabilities are called divergence. If the inertial forces are taken into account, a dynamic instability rises which is known as flutter. The former instabilities are the most common aeroelastic phenomena which can happen to any aircraft or elastic structure in contact with aerodynamic forces. In this work the aeroelastic instabilities of a composite plate wing are studied and the main objective is to try to avoid these events during the flying range of the structure. The optimisation of composite laminates in order to avoid aeroelastic instabilities (maximise the flutter velocity), is called aeroelastic tailoring and has been the subject of study in literature [1], [2], [3].

Aeroelastic tailoring can be an efficient manner to obtain an optimal design for the composite laminate. On the other hand, the manufacturing of this optimal case can be the source of multiple parametric uncertainties [4], such as uncertainties over ply angles and thicknesses [5]. It is therefore necessary to consider these uncertainties during the optimisation process [6] which has for objective to optimise the stochastic response of the aeroelastic system.

In order to obtain this stochastic response, direct uncertainty quantification (UQ) methods such as Monte Carlo Sampling (MCS) or Latin-Hypercube Sampling (LHS) methods can be used. These methods require a large number of evaluations and can become very costly particularly in an optimisation framework. One way to overcome the high computational cost during this study is to use surrogate models. The latter can reduce the number of evaluations and can approximate accurately the stochastic response of the system. While machine learning methods are very efficient during the UQ and optimisation processes, they cannot emulate accurately the response of a discontinuous surface. The flutter velocity being a discontinuous function of the composite material properties, it cannot be directly approximated using a surrogate model. There are multiple ways to overcome this issue, such as using clustering in order to separate different regions of the response surface and emulate them separately using the intended surrogate model. While this method is used and approved by [5], it can be very costly in an optimisation framework. In this work, a change in the formulation of the optimisation problem has been considered using a new variable suggested by [6] as the optimisation objective. The new variable is called the *stability margin* (Λ). It depends on the eigenvalues of the aeroelastic system which are a continuous function of the composite material properties. The composite laminate is described using the ply angles that are also used as the optimisation variables. On the other hand the laminate considered in this study has 16 plies meaning that considering one or two uncertain parameters per layer, can lead to 16 to 32 uncertain parameters. This number of uncertain parameters gives place to the *curse of dimensionality* while working with a surrogate model. This issue is resolved by the use of a set of variables called the polar parameters. The latter is a set of 6 parameters that can describe any property of any given composite laminate. Using the aeroelastic solver, the polar parameters and the designated surrogate model, the stochastic optimisation process is modelled. A Reliability-Based Design Optimisation (RBDO) is conducted meaning that the objective of the process is to reduce the probability of failure.

The RBDO has efficiently optimised the aeroelastic behaviour of the composite structure while obtaining a reliable design. However the investigation has been conducted for the classical uni-directional composite laminate meaning that each ply has one given fibre direction and therefore the laminate has a constant stiffness. The aeroelastic behaviour of the composite structure can be further optimised using variable stiffness laminates. There are multiple ways to design such a laminate and in this work the tow-steered method has been chosen. In these types of materials the direction of the fibres per layer and consequently their stiffness is variable. This process yields to the design of stronger materials with higher aeroelastic performance [7], [8], [9].

2 Work description

In order to obtain the aeroelastic response of the structure presented in figure 1 with properties described in table 1, the structure and the aerodynamics have to be modelled. The structure was modelled using the Finite Element Method (FEM) projected over the modal basis and the unsteady aerodynamic forces are obtained using the Doublet Lattice Method (DLM) [10].

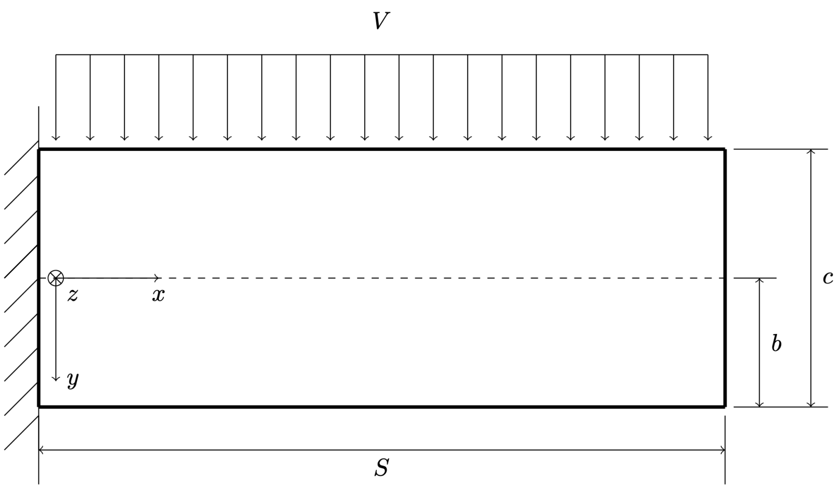

FIGURE 1 – Scheme of the cantilevered plate wing

TABLE 1 – Wing geometry and material properties of AS4/3502 UD layer

$E_1[GPa]$	$E_2[GPa]$	$G_{12}[GPa]$	$\nu_{12}[-]$	$\rho[kg/m^3]$	Half span $S[m]$	Chord $c[m]$	Ply thickness $t[mm]$
138.0	8.96	7.1	0.3	1600	0.3048	0.0762	0.1

Both structure and the aerodynamic models are coupled to create the aeroelastic problem. The eigenvalue problem of the aeroelastic system (equation 1) has been solved in the Laplace domain using the p-k method in order to obtain the aeroelastic damping and frequency for a given velocity (equation 2).

$$([\mathbf{Q}] - s[\mathbf{I}])\{\bar{\alpha}\} = 0 \tag{1}$$

$$s = g \pm i\omega \tag{2}$$

The composite laminate was modelled using the Classical Laminated Plate Theory (CLPT) (equation 3) and its properties have been expressed using polar parameters [11].

$$\begin{bmatrix} \mathbf{n} \\ \mathbf{m} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix} \begin{bmatrix} \varepsilon \\ \kappa \end{bmatrix} \tag{3}$$

There are six Polar Parameters (R_K, R_1, T_0, T_1, Φ_0, Φ_1) that can describe a given. tensor (such as the rigidity tensor). These parameters can be used to express different properties and elastic symmetries of the composite materials such as orthotropy : $\Phi_0 - \Phi_1 = K\frac{\pi}{4}$: $R_K = (-1)^K R_0$, R_1, Φ_1.

Once the aeroelastic response is obtained, it can be used in the optimisation framework. One way to conduct the optimisation process is the deterministic aspect where the flutter velocity (V_f) is maximised.

$$\begin{aligned} \underset{R_K, R_1}{\text{maximize}} \quad & V_f \\ \text{subject to} \quad & -(R_K/R_0^{BL}) + 2((R_1/R_1^{BL})^2) - 1 \leq 0 \end{aligned} \tag{4}$$

Equation 4 reads the deterministic optimisation problem of the flutter velocity V_f in an orthotropic domain. The response surface and the optimal case obtained during this process is presented in figure 2. The presence of the discontinuity on the response surface is observed. It has to be noted that the optimal case is placed next to this discontinuity which can have remarkable impact on the stochastic behaviour of this case under parametric uncertainties.

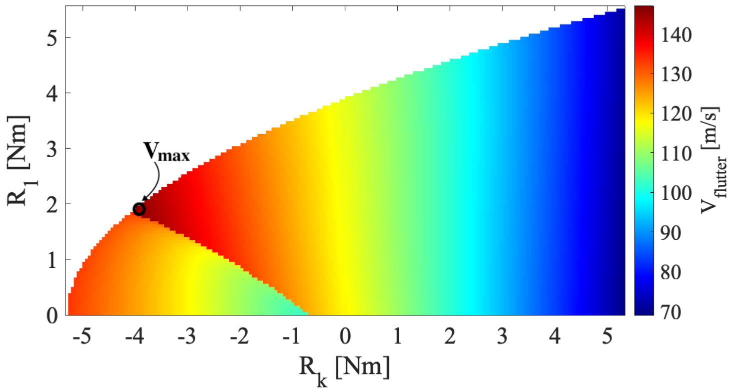

FIGURE 2 – The orthotropic response surface of the flutter velocity as a function of the anisotropic polar parameters R_k and R_1 [11].

Considering a 5° uncertainty over the ply angles of the optimal case, the probability density function presented in figure 3 is obtained.

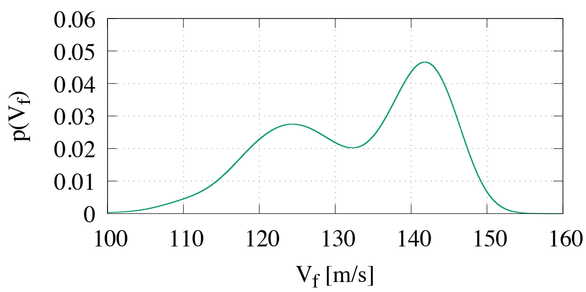

FIGURE 3 – Pdf of the flutter velocity obtained by an uncertainty propagation of 5° over the optimal layup in an orthotropic domain

The pdf of the V_f shows a bi-modal behaviour which corresponds to velocities on each side of the discontinuity on the response surface. It needs to be noted that the optimal V_f obtained during the optimisation is 147 m/s which corresponds to the velocities of the first peak on the pdf. On the other hand the second peak in the lower velocities has a significantly high probability which can fall within the flying margin of the structure and can cause severe damages to the latter.

In order to avoid the second peak over the lower velocities, a new optimisation problem has been formulated which has for objective to reduce the probability of V_f occurring in velocities lower than a given design velocity V_{design} (equation 5).

$$\underset{\theta \in \Theta}{\text{minimize}} \quad P(V_f < V_{design}) \tag{5}$$

As discussed before, this formulation, while being efficient, cannot be used as the optimisation problem because the V_f cannot be approximated on a discontinuous surface using the surrogate models. It is therefore, necessary to reformulate the problem using a new variable. The stability margin (Λ) is obtained using the aeroelastic damping of the structure which are continuous functions of the composite material properties. It is defined as the opposite of the maximum value of the aeroelastic damping at a given velocity (euqation 6).

$$\Lambda = -max \quad g(\theta, V_{design}) \tag{6}$$

Using this new variable, the optimisation problem reads (equation 7) :

$$\underset{\theta \in \Theta}{\text{minimize}} \quad P(\Lambda(\theta, V_{design}) < 0) \tag{7}$$

Hence, a Reliability Based Design Optimisation (RBDO) has been carried out considering an uncertainty of $\sigma = 5^\circ$ over the ply angles. Where Θ represents the ply angles which vary between -90° to -90° with an increment of 5° and V_{design} corresponds to the chosen velocity over which the aeroelastic eigenvalue system is solved. The optimisation problem is solved using the Genetic Algorithm (50 individuals per generation) and a Gaussian Process Regression (GPR) as the surrogate model (30 training samples). Multiple studies with different V_{design} have been tested and a comparison between an optimal case obtained by the RBDO using $V_{design} = 125m/s$ is compared to the initial deterministic optimal case in figure 4.

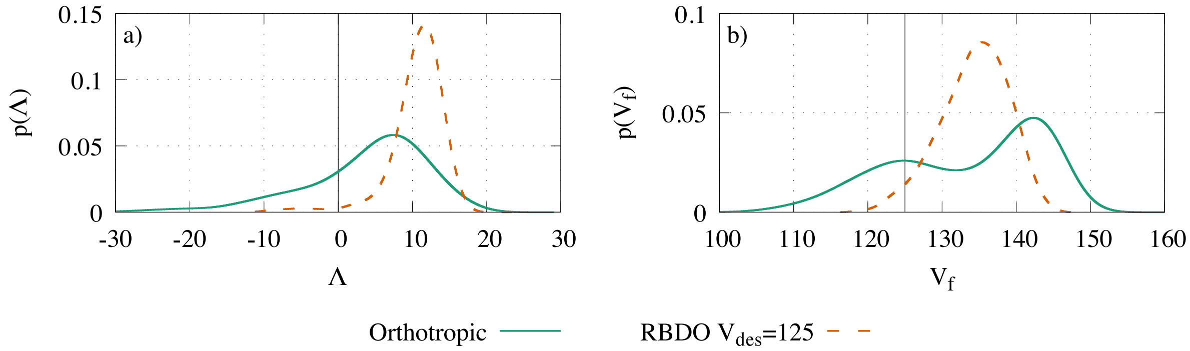

FIGURE 4 – Comparison of the pdf of stability margin in panel (a) and velocity in panel (b) for the RBDO case obtained using a $V_{design} = 125\ m/s$ and the initial optimal deterministic case obtained in an orthotropic domain

The results show a reduction in the probability of failure meaning the probability of having negative stability margin ($P(\Lambda(\theta, V_{design}) < 0)$). These results have been presented during the WCCM & ECCOMAS 2020 conference and want to be developed for a larger range of configurations such as swept and tapered wings.

The optimisations conducted using the uni-directional laminates show encouraging results but they can be further increased using variable stiffness materials [12], [13]. The tow-steered laminates have thus been employed to carry out deterministic optimisation results. The polar parameters have been used as optimisation variables and B-spline surfaces are employed to interpolate the variation of the polar parameters throughout the structure. Different polar parameters have been considered separately as the optimisation variables and have been altered through-out the structure either in one direction (span-wise) or both directions (chord-wise and span-wise). The first polar parameter considered was Φ_1 which represents the direction of the orthotropic axis. R_K and R_1 have been consecutively optimised throughout the structure in order to find the best combination with the maximum flutter velocity. Figure 5 shows the variation of R_1 in span-wise direction which has increased V_f to 152 m/s.

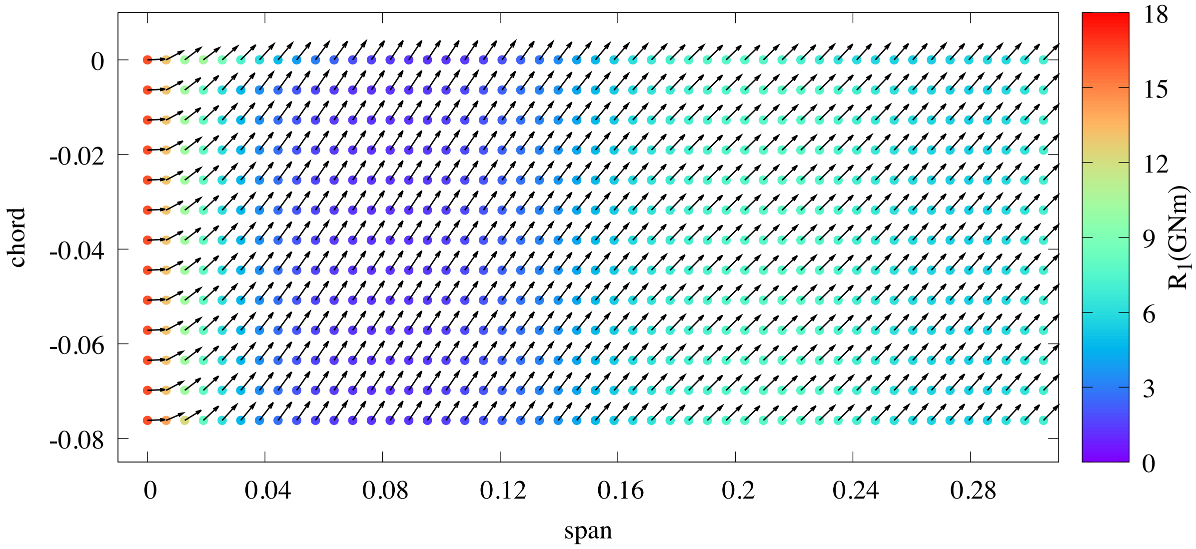

FIGURE 5 – Variation of R_1 over the structure along the span.

Results on the deterministic optimisation over straight and swept wings and some of the Tow-steered cases have been presented in the Aeroelasticity 2021 conference. Broader cases including different configurations and a larger optimisation domains are being studied.

3 Futur work

Variable stiffness composites are as well subject to parametric uncertainties. In this case, the uncertainty considered cannot be presented as a random variable. The variation of the fibre orientation, creates a random field over the structure, in a manner that the variation of on angle can influence other nodes around it. For this reason, the Karhunen-Loeve expansion needs to be considered in order to create a random process which allows the propagation of parametric uncertainties and eventually stochastic optimisation of variable stiffness composites.

Références

[1] Masaki Kameyama and Hisao Fukunaga. *Optimum design of composite plate wings for aeroelastic characteristics using lamination parameters.* Computers & structures, 85(3-4) :213–224, 2007.

[2] D. J. Mourey, *Study of the feasibility aspects of flight testing an aeroelastically tailored forward swept research wing on a BQM-34F drone vehicle*, Contractor Report CR-159149, National Aeronautics and Space Administration, 1979.

[3] T. A. Weisshaar, *Aeroelastic Tailoring of Forward Swept Composite Wings*, Journal of Aircraft 18 (1981) 669–676.

[4] C. Scarth, J. E. Cooper, P. M. Weaver, and G.H.C. Silva. *Uncertainty quantification of aeroelastic stability of composite plate wings using lamination parameters.* Composite Structures, 116 :84–93, September 2014. ISSN 02638223.

[5] Christian Nitschke, Angela Vincenti, and Jean-Camille Chassaing. *Influence of stochastic perturbations of composite laminate layups on the aeroelastic flutter of a cantilevered plate wing.* Composite Structures, 220 :809–826, 2019.

[6] Carl Scarth and Jonathan E Cooper. *Reliability-based aeroelastic design of composite plate wings using a stability margin. Structural and Multidisciplinary Optimization*, 57(4) :1695–1709, 2018.

[7] Stodieck, Olivia, et al. *Improved aeroelastic tailoring using tow-steered composites.* Composite Structures 106 (2013) : 703-715.

[8] Brooks, Timothy R., and Joaquim RRA Martins. *On manufacturing constraints for tow- steered composite design optimization.* Composite Structures 204 (2018) : 548-559.

[9] Haddadpour, Hassan, and Zahra Zamani. *Curvilinear fiber optimization tools for aeroelas- tic design of composite wings.* Journal of Fluids and Structures 33 (2012) : 180-190.

[10] Aditya Kotikalpudi. *Body freedom flutter (bff) doublet lattice method (dlm)*. 2014.

[11] G. Verchery. *Les invariants des tenseurs d'ordre 4 du type de l'élasticité. In Comportment Mécanique des Solides Anisotropes*, volume 115, pages 93–104, Villard-de-Lans, 1979. Editions du CNRS, Paris.

[12] GA Fiordilino, MI Izzi, and M Montemurro. MontemurroA general isogeometric polar approach for the optimisation of variable stiffness composites : Application to eigenvalue buckling problems. Mechanics of Materials, 153 :103574, 2021.

[13] Marco Montemurro and Anita Catapano. MontemurroA general b-spline surfaces theoretical framework for optimisa- tion of variable angle-tow laminates. Composite Structures, 209 :561–578, 2019.