ROBUST AEROELASTIC OPTIMIZATION OF TOW-STEERED COMPOSITE PANELS

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ABSTRACT

Due to recent advances in automated manufacturing technology, the so-called tow-steered laminates, in which the fibers in the layers are deposited following arbitrary curvilinear paths, have become viable. A number of previous studies have demonstrated that tow-steered laminates can exhibit improved structural performance in terms of bending, buckling, vibration and aeroelastic behavior, as compared to traditional unidirectional laminates. The classical design strategy to cope with aeroelastic stability criteria, known as aeroelastic tailoring, consists essentially in stacking unidirectional fiber plies of different orientations. The application of aeroelastic tailoring to two-steered laminates potentially opens new possibilities of performance improvement, since the fiber trajectories can be dealt with as additional design variables. On the other hand, the performance of composite structures is strongly influenced by manufacturing imperfections, which, in this study are regarded as uncertainties. The present paper is devoted to the numerical study of the influence of uncertainties affecting the fiber trajectories on the aeroelastic stability of tow-steered composite panels, including: stochastic sensitivity analysis, aiming at evaluating the impact of uncertainties on the flutter instability boundaries, and stochastic robust optimization, intended for minimizing this impact on the optimized aeroelastic behavior. The Classical Lamination Theory is adopted to model the layered composite plates, duly adapted to account for curvilinear fiber trajectories on each layer. The aeroelastic model is based on the Ritz method, with the aerodynamic forces modeled according to the supersonic piston theory. The flutter stability boundaries for designs obtained by using deterministic and stochastic optimization of a tow-steered plate are compared., confirming improvements in terms of robustness against perturbations in the fiber trajectories.

1 INTRODUCTION

Panel flutter is an instability condition caused by the interaction of inertial, elastic and aerodynamic forces generated by the interaction of elastic plate-like or shell-like structures with surrounding supersonic airflows [1].

Recent achievements in automation have been leading to the continuous improvement of manufacturing processes of composite materials. In particular, Automated Fiber Placement (AFP) process currently enables to manufacture the so-called Variable Stiffness Panels (VSP), which are characterized by non-uniform fiber distribution over the plies. A particular type of VSP are tow-steered plates (TSP), in which the fibers are deposited following curvilinear paths. As compared to traditional unidirectional composite laminates, TSP can potentially be designed more effectively to comply with static, buckling, vibration and aeroelastic requirements [2]. On the other hand, the performance of TSPs is strongly influenced by manufacturing imperfections, which can be considered random uncertainties [2]. In the present paper, the influence of uncertainties affecting the fiber trajectories on the aeroelastic stability of tow-steered composite panels is numerically appraised, including stochastic sensitivity analysis and stochastic robust optimization.

2 AEROELASTIC MODEL OF TOW-STEERED COMPOSITE PLATES

The *i*-th ply of a rectangular TSP of dimensions $s \times c$ is depicted in Fig. 1, in which θ indicates the fiber angle, assumed to vary according to:

$$\theta_i(x) = \bar{\theta}_i + \frac{\theta_s - \theta_0}{s} x + \theta_0 \tag{1}$$

where $\bar{\theta}_i$ is the orientation angle of the ply and θ_0, θ_s are, respectively, the fiber angles at $x = 0$ and $x = s$. In Fig. 1, U indicates the airflow velocity.

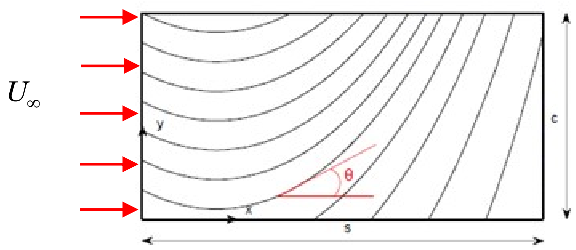

Fig. 1. Illustration of a typical ply of a tow-steered laminate.

Assuming that the laminate is sufficiently thin, it is modeled according to the Classical Lamination Theory (CLT), and the transverse displacements $w(x,y,t)$ are assumed to be constant through the plate thickness. Moreover, each ply is assumed to be in plane strain state, and other hypotheses of Kirchhoff's plate theory are adopted. Neglecting in-plane loads, the relations between moments $\tilde{\boldsymbol{M}} = \begin{bmatrix} M_x & M_y & M_{xy} \end{bmatrix}^T$ and curvatures $\tilde{\boldsymbol{\kappa}} = \begin{bmatrix} \kappa_x & \kappa_y & \kappa_{xy} \end{bmatrix}^T$ for the laminate are expressed as [3]:

$$\tilde{\boldsymbol{M}} = \boldsymbol{D}(\theta_1, \theta_2, \ldots)\tilde{\boldsymbol{\kappa}} \tag{2}$$

It can be shown that matrix $\boldsymbol{D}$ can be expressed in terms of a set of *lamination parameters*, defined as follows (h is the thickness of the laminate) [3].

$$\{W_1,W_2,W_3,W_4\} = \frac{12}{h^3}\int_{-h/2}^{-h/2} z^2 \{cos(2\theta),sin(2\theta),cos(4\theta),sin(4\theta)\}\, dz \tag{3}$$

As for the aerodynamic loads, the pressure is modeled as follows, according to the method proposed by Ashley [4], known as first order piston theory (ρ is the fluid density and M_∞ is the Mach number):

$$\Delta P = \lambda \frac{\partial w}{\partial x} = \frac{\rho_\infty U_\infty^2}{\sqrt{M_\infty^2 - 1}} \frac{\partial w}{\partial x} \tag{4}$$

According to the Assumed-Modes approach, the transverse displacement field is approximated as a linear combination of trial functions, as follows:

$$w(x,y) = \sum_{i=1}^{m}\sum_{j=1}^{n} r_i\phi_i(x)\cdot s_j\varphi_j(y) = \sum_{k=1}^{N} q_k\eta_k(x,y) = \boldsymbol{N}(x,y)\boldsymbol{q} \tag{5}$$

After formulating the strain and kinetic energies and applying Lagrange's Equations, the equations of motion are found in the form of set of linear second-order ordinary differential equations, to which the following eigenvalue problem is associated:

$$(\lambda \boldsymbol{K}_a + \boldsymbol{K} - \mu \boldsymbol{M})\boldsymbol{q} = \boldsymbol{0}, \tag{6}$$

Stability analysis is performed by inspecting the eigenvalues μ for increasing values of the parameter λ, associated to the flow speed.

3 SENSITIVITY ANALYSIS AND ROBUST OPTIMIZATION

The sensitivity index of the response y with respect to a random parameter p_i is defined as (E(.) and σ^2(.) denote the expected value and variance, respectively):

$$S_i = \frac{\sigma^2\left[E(y|p_i)\right]}{\sigma^2\left[E(y)\right]}, \tag{7}$$

In evaluating (7), Polynomial Chaos Expansion (PCE) is used based on the use of Hermite polynomials for the expansion of Gaussian random variables.

The multi-objective robust optimization problem is defined as follows:

$$\begin{aligned} \text{Minimize: } & J_1(\boldsymbol{p}) = -E(U_{flutter}) \\ & J_2(\boldsymbol{p}) = \sigma^2(U_{flutter}) \ , \\ \text{Subjected to } & \boldsymbol{p}_{min} \le \boldsymbol{p} \le \boldsymbol{p}_{max} \end{aligned} \tag{8}$$

where $\boldsymbol{p}$ is the vector of design parameters.

The construction of Pareto front for non-dominated optimal solutions is carried-out by using a multi-criteria version of Differential Evolution (DE) optimization method.

The deterministic optimization is defined when the objective function is simply $J(\boldsymbol{p}) = -U_{flutter}$.

4 NUMERICAL RESULTS

A composite rectangular simply supported plate with *s*=400 mm, *c*=300 mm, consisting of eight graphite/epoxy plies of uniform thickness *t*=0.19 mm. The mechanical properties of the plies are: $E_1 = 129.50$ GPa, $E_2 = 9.37$ GPa, $G_{12} = 5.24$ GPa, $\mu_{12} = 0.38$, $\rho = 0.38$. As a baseline configuration one adopts a unidirectional (unsteered) laminate with stacking sequence $\left[0 \quad 45 \quad -45 \quad 90\right]_s$. For this configuration, the evolution of the natural frequencies as function of parameter λ is depicted in Figure 2; the coalescent of two of those frequencies indicates the onset of instability (flutter) at $\lambda = 2.05 \times 10^5$.

For the tow-steered configuration, for which the stacking sequence of the baseline plate was also adopted, the sensitivity analysis for parameters $\left(\theta_0, \theta_s, E_1, E_2, G_{12,} \mu_{12}, \rho\right)$ leads to the results presented in Figure 3. From these results, parameters $\left(\theta_0, \theta_s\right)$ were chosen as optimization design variables. Table 2 enables to compare the results of deterministic and robust optimizations.

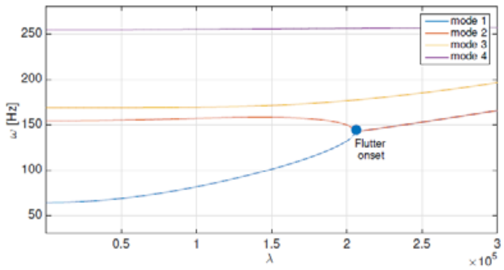

Figure 2. Evolution of the natural frequencies for the baseline configuration.

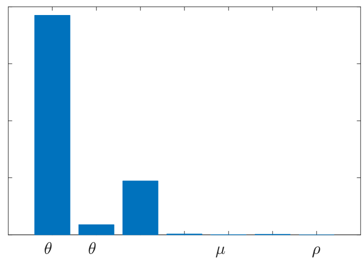

Figure 3. Sensitivity index for the two-steered composite plate.

	Deterministic sol.	Robust sol.
θ_0, θ_s **(deg.)**	−17.72, 5.12	−21.90, 3.22
J	2.17×10^5	-
J_1, J_2	-	2.14×10^5, 3.58×10^3

Table 2. Deterministic and robust optimization solutions

The difference between both solutions is highlighted in Figure 4, in terms of the PDFs of the using PCE. It can be seen that, as compared to the deterministic solution, the robust solution presents lower mode value of the flutter speed, but a smaller dispersion.

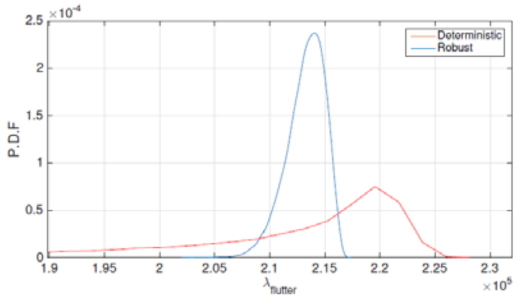

Figure 4. PDFs of the flutter velocity for deterministic and robust optimization solutions.

5 CONCLUSIONS

The influence of uncertainties affecting the tow angles of laminate composite panels on flutter speed of these later was assessed, both in terms of stochastic sensitivity analysis combine with Polynomial Chaos Expansion and robust optimization. The study was motivated by the need of dealing with imperfections introduced by the manufacturing process. The optimization results demonstrated that the deterministic optimization was capable of improving the flutter speed, but the optimal solution have shown to be quite sensitive to random perturbations in the design variables. On the other hand, robust solutions extracted from the set of solutions on the Pareto front demonstrated improvements in terms of the robustness with respect to those perturbations. The numerical strategy conceived have shown to be quite adequate in terms of computational burden.

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