Journal of Fluids and Structures 51 (2014) 292–312

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Aeroelastic tailoring of a plate wing with functionally graded materials

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ARTICLE INFO

Article history:
Received 10 March 2014
Accepted 13 September 2014
Available online 23 October 2014

Keywords:
Functionally graded materials
Aeroelastic tailoring
Plate wing
Doublet Lattice Method
Flutter
Genetic algorithm

ABSTRACT

A functionally graded material (FGM) provides a spatial blend of material properties throughout a structure. This paper studies the efficacy of FGM for the aeroelastic tailoring of a metallic cantilever plate-like wing, wherein a genetic algorithm provides Pareto trade-off curves between static and dynamic aeroelastic metrics. A key comparison is between the effectiveness of material grading, geometric grading (i.e. plate thickness variations), and using both simultaneously. The introduction of material grading does, in some cases, improve the aeroelastic performance. This improvement, and the physical mechanism upon which it is based, depends on numerous factors: the two sets of metallic material parameters used for grading; the sweep of the plate; the aspect ratio of the plate; and whether the material is graded continuously or discretely.

1. Introduction

Achieving the lightest possible structure is fundamental to aircraft design. However, the design must comply with structural strength and dynamic instability criteria, both of which are related to the wing's aeroelastic response in flight. Aeroelastic tailoring is a passive approach to achieve lightweight airframe designs through load alleviation and tuned dynamic properties. Aeroelastic tailoring has been defined as "*the embodiment of directional stiffness into an aircraft structural design to control aeroelastic deformation, static or dynamic, in such a fashion as to affect the aerodynamic and structural performance of that aircraft in a beneficial way*" (Shirk et al., 1986). In addition to stiffness, mass distribution also has an effect on the dynamic properties of a structure, although it is typically considered less during initial design efforts and more to mitigate harmful unforeseen dynamics found later in the design process. Today, enhanced fabrication processes, advanced materials, and unique structural designs offer new design possibilities for aeroelastic tailoring that have not been fully exploited. A review of the current state-of-the-art in aeroelastic tailoring is given by Jutte and Stanford (2014), and includes novel design concepts such as variable-stiffness plates and plies, selectively reinforced materials, curvilinearly-reinforced members and topologically-optimized cross-sections. The focus of the current paper is one such novel aeroelastic tailoring concept: functionally graded materials (FGM).

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http://dx.doi.org/10.1016/j.jfluidstructs.2014.09.008
0889-9746/

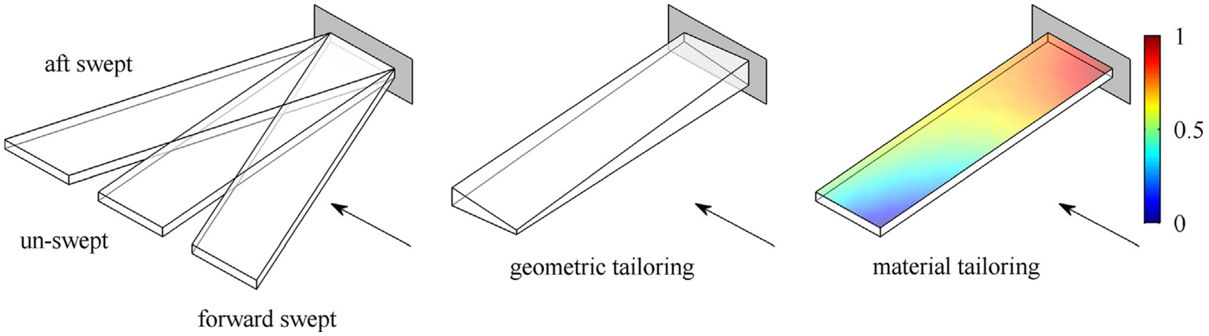

Fig. 1. Overview of the study.

Functionally graded materials have continuously varying properties by spatially varying the distribution of two (or more) materials, which facilitates designs with tailored stiffness within a continuous metallic structure (Miyamoto et al., 1999). New manufacturing processes, such as electron beam freeform fabrication (EBF^3), an additive manufacturing process (Taminger and Hafley, 2003), are helping to enable the fabrication of functionally graded metals and making FGMs accessible to aircraft design. FGMs offer two potentially advantageous design capabilities. First, they enable continuous changes in material properties (elastic modulus, density, yield stress, etc.) throughout a structure, allowing local properties to be tuned. Second, they enable changes in structural stiffness without necessarily requiring a geometric change in the structural geometry, such as an increase in thickness.

In spite of their potential to improve the state-of-the-art in high-performance aircraft structures, few examples of FGMs in an aerospace setting are available in the literature (Birman and Byrd, 2007). Most of the existing work details the use of FGM for elastic panels subject to supersonic flows (and thus, aerodynamic heating): see Marzocca et al. (2011), Navazi and Haddadpour (2007) and Sohn and Kim (2008). Gradual material grading is particularly beneficial to high-temperature applications since it can eliminate discrete changes in the coefficient of thermal expansion, which would introduce stress concentrations at material boundaries (Marzocca et al., 2011). FGMs have been shown in these papers to improve the aerothermoelastic panel flutter boundaries as well. For subsonic structures, Librescu and Maalawi (2007) use material grading to optimize the material distribution of a cantilevered wing (maximization of torsional divergence stability under a mass constraint). Linear, parabolic, and piecewise material grading distributions along the wing span are all considered. Although the paper used fiber volume fractions of composite materials (rather than metallic grading, which is the emphasis of the current work), it is notable as one of very few papers that consider subsonic aeroelastic tailoring via material grading. Therefore, the present paper aims to fill a gap in the literature pertaining to FGM-based aeroelastic tailoring, by considering a metallic wing in low-speed (subsonic) conditions.

The model used in the study is a simple plate-like wing clamped at the root and immersed in subsonic flow. The effect of the planform on the optimal design is investigated by varying its sweep angle and aspect ratio. The material grading strategies considered for the FGM are limited to continuous bi-linear distributions of two materials over the wing planform. A discrete material grading strategy is also considered. Bi-linear geometric grading of the wing through plate thickness variation is also considered part of the design space. An overview of the wing planform and geometric and material tailoring strategies is shown in Fig. 1. The aeroelastic performance of the wing is assessed using two metrics: the flutter and divergence speeds (whichever is lower and more critical) and the maximum von Mises failure criteria in the wing resulting from the deformation under a steady flight condition at a specified angle of attack. To evaluate the potential of FGM for aeroelastic tailoring, the aeroelastic performance of uniform material designs are compared to FGM designs, where all wing designs have equal mass. The wing model used in this study is simple and the number of design metrics considered is limited. However, the scope of the study allows us to uncover some physical mechanisms that allow FGM to be exploited for aeroelastic tailoring.

The paper is organized as follows. Section 2 details the aeroelastic model and performance metrics used in the study. Section 3 considers simple FGM and thickness-graded design concepts. A simple parameter sweep is used to demonstrate the changes in aeroelastic physics for different grading strategies. Section 4 considers more complex design concepts and the design space is explored using a genetic algorithm. Section 5 summarizes the main conclusions from the study.

2. Aeroelastic solution methodology

The modeling tools used to characterize the aeroelastic behavior of the plate-wings are described in this section. These tools have been extensively verified against the aeroelastic solvers in NASTRAN, although for brevity details of the verification process have been omitted from the paper. The wing structure is modeled using discrete Kirchhoff triangular (DKT) plate elements (Cook et al., 2002) with consistent mass matrices. The wing is fully clamped at the root (cantilevered). The properties of the functionally graded material are approximated using the rule of mixtures. The percentage of each material within an element is taken as the percentage at the element center. The Doublet Lattice Method (DLM) (Blair, 1992;