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Wing weight model for conceptual design of nonplanar configurations

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ABSTRACT

Unconventional aircraft designs, such as nonplanar wings, are being considered for the next generation of transport aircraft. In order to determine the suitability of such designs, conceptual design tools are needed which are both sensitive to these unconventional configurations and capable of obtaining results rapidly. Wings represent a large contribution to an aircraft's empty weight and there are many commonly used conceptual design tools which can accurately estimate this component's weight for conventional designs. However, nonplanar wings can have very different aerodynamic loadings and structural details so existing models cannot be easily extended to treat these complexities. This paper shows the development of a conceptual-level wing weight model which combines a fully-stressed cross-section method with an equivalent beam finite-element structural solver using loads derived from a nonplanar vortex-lattice method. This model is able to obtain accurate aerodynamic loadings for nonplanar wings and can model the statically indeterminate structure of closed wing configurations. It was shown to be as accurate as current approaches when analyzing conventional wings and it is able to show the details of nonplanar wing structures. This model will enable more meaningful multidisciplinary analyses of both conventional and unconventional wing designs by accurately and rapidly predicting both the weight and internal structural details of these designs.

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1. Introduction

Nonplanar wings are an unconventional aircraft configuration which can enable fuel savings for civil and military transport missions. Such designs can have both aerodynamic and structural advantages which make them appealing for future generations of transport aircraft [17]. When assessing the performance of nonplanar wings, the effects of the wing design on its structural weight has been identified as one of the primary sources of fuel savings of such configurations [33,13,2,3]. Most existing conceptual design tools, however, are not capable of making accurate predictions of nonplanar wing weights.

Existing wing weight models cannot account for the unconventional aerodynamic loading and structural details of nonplanar designs. An example of a nonplanar wing whose overall performance is highly dependent on its structural details is a box-wing. This design consists of a pair of tandem wings whose wing-tips are connected by a third wing segment which acts as both a winglet and a structural member. A box-wing is a design with the lowest theoretical induced drag of any wing configuration [23] though it has more exposed area than a conventional wing and thus higher parasitic drag. This wing configuration is 'closed' i.e. attached to the fuselage at two points, thus the wing is no longer cantilevered. This provides a reduction in the wing-root bending moment, though it increases the projected area of the wing relative to a conventional design. Though the box-wing has a greater planform area than a conventional design, the non-cantilevered structure may lead to lower structural weight. This illustrates why an accurate understanding of the factors affecting wing weight is critical in determining whether a nonplanar wing is superior to other competing designs.

There are various 'classes' of wing weight prediction models which are differentiated based on the amount of design information required for the analysis; the taxonomy of such models is described in [32]. Class II models predict the weight of the wing based on a small set of high level parameters such as the planform area, aspect ratio and sweep. These models are appropriate for very early design stages; Raymer [25], Howe [12] and Roskam [26] provide such models for conventional aircraft. As these models are based more on empirical relations than on physical principles, they cannot be extended to predict unconventional, nonplanar, designs. Jemitola et al. performed a finite element analysis of a variety of box wing designs [15] and used this approach to create a class II weight prediction model for a box-wing aircraft [14]. This model is very useful in the conceptual design of box-wings but cannot be applied to other nonplanar or conventional wing designs.

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Nomenclature

ℓ	Length of airfoil section skin	ft
A	Area of airfoil section boom	ft^2
dA	Area subtended by airfoil skin section	ft^2
F	Axial force	lbf
I	Area moment of inertia	ft^4
J	Polar moment of inertia	ft^4
L	Finite element length	ft
M	Bending moment	ft lbf
n_{pan}	Total number of FE elements	
q_i	Open-section shear flow	lbf/ft
q_o	Closed-section shear flow	lbf/ft
T	Torsional moment	ft lbf
t	Structural thickness	ft
V	Shear force	lbf
W	Weight	lbf

Subscripts

alw	allowable
i	airfoil section boom index
n	finite element index
y	yield

Abbreviations

MTOW	Maximum Takeoff Weight	lbf

Symbols

$\eta_{a.f.}$	Normalized effective airfoil thickness	
$\eta_{a.s.}$	Normalized chord-wise position of aft spar	
$\eta_{f.s.}$	Normalized chord-wise position of fore spar	
ϕ	Bending material constant	ft^2/ft
ρ	Material density	lbf/ft^3
σ	Normal stress	lbf/ft^2
τ	Shear stress	lbf/ft^2
ζ	Distance of airfoil section boom to section center of gravity	ft

There are more advanced class II models, termed class II-1/2 by some authors [7]. Such models require more detail about the wing's design but the analysis is driven more by the underlying physics of the wing than by empirical modeling and the results are more sensitive to design choices. Examples of such models are those of Torenbeek [31], Ardema et al. [4], Liu and Anemaat [19], Elham et al. [7] and Petermeier et al. [22]. Though the exact details of these models differ, they all follow roughly a similar approach, itemized below:

- Determine the aerodynamic loads at one or more critical operational points.
- Calculate the local bending moments and shear forces.
- Determine the allowable stresses.
- Create a relationship between the wing box size and the maximum local stresses.
- Size the wing box to be fully stressed at the most critical design point, with applicable safety factors.
- Add additional weight to account for structural components not associated with the primary structure

More complex than these methods are class III models which make use of high fidelity computational fluid dynamics (CFD) and structural finite element (FE) analysis software to analyze the details of the flow over the wing and the stresses within the wing structure. Individual spars, ribs, and stiffened skins are modeled in the FE analysis and the loads are obtained from the surface pressure distribution calculated from viscous, compressible CFD analyses. The state of the art of such methods [18,16] provides a great deal of information on the aircraft structure and aerodynamics. Due to the computing resources required for such analyses, such models are most suitable to multidisciplinary analyses of a narrow range of aircraft configurations. In more general multidisciplinary studies which consider multiple, unconventional, aircraft configurations, the minimum structural weight of the wing must be estimated on the order of seconds. Though various structural idealizations can greatly simplify the full FE model of the wing, the time taken to obtain an estimate of wing weight from a class III method limits their use for most conceptual studies of unconventional aircraft designs.

The weight prediction model presented in this paper is considered class II-1/2 in terms of the level of detail required for the analysis and the necessary computational resources. The method follows the approach of class II-1/2 methods with one notable difference, it uses an equivalent beam FE model of the wing to determine internal forces and moments rather than simply integrating the aerodynamic loading along the span. The weight of the wing was estimated by using the internal forces to calculate the material required for a fully stressed structural cross-section. Gallman and Kroo [8] examined both fully stressed and minimum weight optimization approaches to weight prediction and found that the fully stressed method achieved results within 1–2% of the optimization with an order of magnitude lower computational costs.

The methodology for this model will be described in greater detail in Section 2. The results of this model, applied to a conventional aircraft, will be examined in Section 3.1. The model will then be applied to a wider selection of conventional transport aircraft and the results compared to a selection of class II and class II-1/2 methods in Section 3.2. The model will then be used to examine the structural details of a representative box-wing aircraft in Section 3.3 to better understand the effects of structural considerations on such designs. Possible extensions to this model are discussed in Section 4 and the overall performance of this method will be summarized in Section 5.

2. Methodology

This section presents the formulation of the wing weight prediction model. The wing is represented as a series of trapezoidal lifting segments. Some of the parameters which can vary for each segment are: span, sweep, taper, dihedral, thickness and incidence. Fig. 1 shows a wing made up of two lifting segments which has been discretized into several spanwise panels. Each panel is represented as a vortex ring in the aerodynamic analysis and as an equivalent-beam finite element in the structural analysis. The properties of each equivalent beam finite element are derived from a cross section with sufficient material to be fully stressed under the internal forces and moments located at the middle of the finite element.

The fully stressed analysis algorithm determined the structural thicknesses at each spanwise station required for the worst case aerodynamic loadings on the wing. The analysis considered multiple loading cases, each case consisting of the following parameters: a set of atmospheric conditions, a maneuver load factor, an inertial load factor, a steady flight target lift coefficient and a fuel load.

The aerodynamic forces for each load condition were calculated using the model described in Section 2.1. The aerodynamic loads

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