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Comparison of box-wing and conventional aircraft mission performance using multidisciplinary analysis and optimization

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A B S T R A C T

Box-wing aircraft designs have the potential to achieve significant reductions in fuel consumption. Closed non-planar wing designs have been shown to reduce induced drag and the statically indeterminate wing structure can lead to reduced wing weight. In addition, the streamwise separation of the two main wings can provide the moments necessary for static stability and control, eliminating the weight and aerodynamic drag of a horizontal tail.

Proper assessment of the disciplinary interactions in box-wing designs is essential to determine any realistic performance benefits arising from the use of such a configuration. This study analyzes both box-wing and conventional aircraft designed for representative regional-jet missions. A preliminary parametric investigation shows a lift-to-drag ratio advantage for box-wing designs, while a more detailed multidisciplinary study indicates that the requirement to carry the mission fuel in the wings leads to an increase of between 5% and 1% in total fuel burn compared to conventional designs. However, the multidisciplinary study identified operating conditions where the box-wing can have superior performance to conventional aircraft despite the fuel volume constraint.

1. Introduction

The box-wing planform geometry is a nonplanar wing design which can achieve significant reductions in induced drag per unit of planform area [1]. The box-wing geometry consists of two main lifting surfaces connected at their tips by a third, near vertical, lifting surface, see Fig. 1. In addition to aerodynamic benefits, the closed, nonplanar wing design forms a statically indeterminate structure which may lead to a lighter wing [2]. If the two main lifting surfaces of the box-wing design have sufficient longitudinal separation, they can create the moments necessary for stability along this axis and eliminate the need for a horizontal tail as well as its associated structural weight and aerodynamic drag.

An unconventional nonplanar wing geometry presents a conceptual design challenge, as analysis tools used at the conceptual stage may not capture all the *physics processes* [4] which influence the performance of the aircraft. In addition, as no box-wing transport aircraft has entered service, there is no obvious initial point in the design space of the box-wing geometries to investigate.

Earlier investigations of aircraft with a box-wing planform have considered one or two of these important design disciplines in isolation. A thorough review of previous work on box-wing aircraft is given by Cavallaro and Demasi [5]. The box-wing aircraft design was first proposed by Prandtl in 1918 [6]. Further theoretical investigations were performed by von Kármán and Burgers [7]. These two studies sought the planform shape with the lowest induced drag (neglecting airfoil section effects) given a fixed span and maximum separation between wings. This optimum planform shape was a box-wing with a spanwise circulation distribution where equal lift was carried on each wing and the spanwise loading on the horizontal surfaces was a combination of a constant circulation plus elliptical distribution with the circulation decreasing linearly along the vertical segments, as shown in Fig. 2. More recent studies have claimed that this is not the only spanwise loading which can achieve minimum induced drag [8,9]. These authors showed that the constant component of the spanwise circulation can vary between the fore and aft wings while still achieving minimum induced drag, allowing the two horizontal wings to generate different lift forces. The effects of parasitic drag and the complex flow which develops at the joints between lifting surfaces were examined in two studies which performed a high-fidelity aerodynamic shape optimization of box-wing designs [10,11]. These studies showed that box-wings can have approximately a 7% advantage in fuel consumption in the cruise phase of the mission [11].

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Nomenclature

Subscripts

1	Fore wing	
2	Aft wing	
α	Sensitivity to angle of attack	/deg
n	Sum of fore and aft wings	

Dimensionless groups

C_D	Aircraft drag coefficient
C_L	Aircraft lift coefficient
C_l	Local lift coefficient
C_W	Aircraft weight coefficient
Re	Reynolds number
C_d	Airfoil drag coefficient
$C_{d_{p0}}$	Airfoil section constant parasitic drag coefficient
$C_{d_{p_1}}$	Airfoil section linear parasitic drag coefficient
$C_{d_{p_2}}$	Airfoil section quadratic parasitic drag coefficient
$C_{l_{max}}$	Airfoil section maximum lift coefficient
C_{l_o}	Airfoil section lift coefficient at zero incidence
C_m	Airfoil section pitching moment coefficient
Ma	Mach number

Acronyms

BLF	Balanced Field Length	ft (0.305 m)
C2OEICG	Second segment OEI climb gradient	
MTOW	Maximum Takeoff Weight	$\mathrm{lb_f}$ (4.44 N)
OEI	One Engine Inoperative	
SFC_T	Thrust specific fuel consumption	1/s
TSSL	Sea-level standard day thrust	$\mathrm{lb_f}$ (4.44 N)

Variables

$\Delta_{c.g.}$	Center of gravity offset	ft (0.305m)
γ	Wing twist angle, relative to aircraft centerline	deg
λ	Wing taper	
ρ	Density	$\mathrm{slug/ft^3}$ (516 $\mathrm{kg/m^3}$)
b	Total span	ft (0.305 m)
$\bar{c}$	Mean aerodynamic chord	ft (0.305 m)
h	Height between lifting surfaces	ft (0.305 m)
L	Lift	$\mathrm{lb_f}$ (4.44 N)
n_{pan}	Number of vortex panels	
n_{seg}	Number of wing segment	
S	Projected Area	$\mathrm{ft^2}$ (0.0930 $\mathrm{m^2}$)
V	Airspeed	ft/s (0.305 m/s)
W	Weight	$\mathrm{lb_f}$ (4.44 N)
$x_{1\rightarrow 2}$	Stagger between lifting surfaces	ft (0.305 m)
a	Speed of Sound	ft/s (0.305 m/s)
α_{mvr}	Aircraft angle of incidence in maneuver	deg
α_o	Incidence at zero airfoil section lift	deg
f_m	Aerodynamic meta-model	
G	Constraint function	
g	Vector of constraints	
R	Mission range	nmi (1.85 km)
T	Thrust	$\mathrm{lb_f}$ (4.44 N)
V	Volume	$\mathrm{ft^3}$ (0.0283 $\mathrm{m^3}$)
$W_{n.g.}$	Weight carried by nose landing gear	$\mathrm{lb_f}$ (4.44 N)
x	Vector of design variables	

Fig. 1. Different nonplanar wing designs. Box-wings are a member of the closed nonplanar wing family [3].

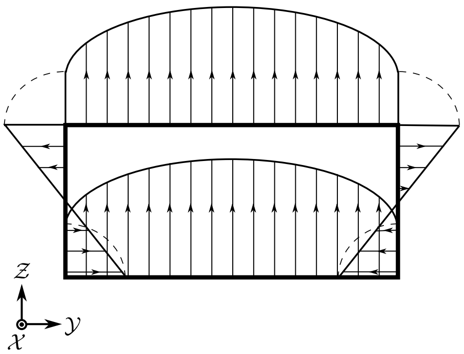

Fig. 2. Optimal spanwise lift distribution for a box-wing aircraft. Adapted from Prandtl [6].

Previous studies which compared the weight of a conventional wing to a joined-wing design showed that when the weight of the main lifting surfaces were compared, the joined-wing did not provide a significant advantage in terms of structural weight [12,13]. However, if the joined-wing was designed such that the horizontal tail could be removed, the total weight of the aircraft's lifting surfaces was reduced. A similar result was found when the wing structure of box-wing designs was considered [14]. This shows an important interaction between the analysis of longitudinal stability and structural weight in box-wing aircraft. When considering the couplings between the disciplines of aerodynamics and structures alone, it was found that the box-wing had a 5% advantage in mission fuel consumption, compared with a conventional design [15].

Previous work has shown that the requirements of static longitudinal stability may impose an aerodynamic penalty on the box-wing design [16]. This study, however, used an induced drag model that may have been overly sensitive to lift imbalance between both wings compared to more recent models [8,9]. Preliminary studies have also been performed on the dynamic stability of box-wing aircraft and have shown that designs which were statically stable would have acceptable handling qualities with a stability augmentation system [17].

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