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Wing shaping concepts using distributed propulsion

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Abstract
Purpose – The purpose of this research is to explore innovative aircraft concepts that use flexible wings and distributed propulsion to significantly reduce fuel burn of future transport aircraft by exploiting multidisciplinary interactions.
Design/methodology/approach – Multidisciplinary analysis and trajectory optimization are used to evaluate the mission performance benefits of flexible wing distributed propulsion aircraft concepts.
Findings – The flexible wing distributed propulsion aircraft concept was shown to achieve a 4 per cent improvement in L/D over a mission profile consisting of a minimum fuel climb, minimum fuel cruise and continuous descent.
Practical implications – The technologies being investigated may lead to mission adaptive aircraft that can minimize drag, and thus fuel burn, throughout the flight envelope.
Originality/value – The aircraft concepts being explored seek to create synergistic interactions between disciplines for reducing fuel burn while capitalizing on the potential benefits of lightweight, flexible wing structures and distributed propulsion.

Keywords Wing shaping, Distributed propulsion, Hybrid electric, Aeroelastic, Electric propulsion

Paper type Research paper

Nomenclature

Symbols

α_c = aeroelastic angle of attack
α = rigid aircraft angle of attack
γ = jig shape twist
Θ = twist distribution
W_x = bending slope
T = thrust
V = true speed
h = altitude
F = specific excess thrust
c = specific fuel consumption
D = total drag
W = aircraft weight
L = lift8

Introduction

Under the Fundamental Aeronautics Fixed Wing Program, the NASA Aeronautics Research Mission Directorate is conducting foundational research to investigate advanced multi-discipline-based concepts and technologies for future aircraft systems. As an exploratory study in 2010, future aircraft designs were investigated that might yield a fuel burn reduction of 70 per cent by 2035. A central focus of the enabling technologies identified were those which reduced operational empty weight of the aircraft with minimal impact on drag.

In 2010, a NASA Innovation Partnership Program study conducted at NASA Ames Research Center identified that active aeroelastic wing shaping control appears to have a potential drag reduction benefit on the order of 3-4 per cent. This initial study lead to a research effort under the Fixed Wing project to investigate concepts and technologies that enable highly flexible aerodynamic surfaces to be elastically shaped in flight by active control of wing twist and vertical deflection to optimize the local angle of attack of wing sections. This results in improved aerodynamic efficiency through drag reduction at cruise (Nguyen, 2010).

In 2011, NASA Glenn Research Center conducted a study which used distributed propulsion embedded along the upper surface of a turboelectric blended wing body concept to increase propulsive efficiency by ingesting the boundary layer on the center fuselage section. Using a hybrid electric propulsion system architecture, the concept achieved between 3 and 7 per cent fuel saving resulting from a three-fold

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increase in bypass ratio and improvements in propulsive efficiency (Felder, Brown, Kim 2011).

To explore the fuel burn reduction potential of combining two technologies into a single airframe, a new modelling and analysis approach was developed for a flexible wing distributed propulsion concept. To adequately capture multidisciplinary interactions, physics-based models were created to better understand the impact on mission performance and to identify potential issues with aero-structural instabilities, particularly flutter.

Methodology

The benchmark vehicle selected for the study is a notional single-aisle, mid-size, 200-passenger aircraft. The geometry of the aircraft is obtained by scaling up the geometry of the NASA generic transport model (GTM) by a scale of 200:11. The GTM is a research platform that includes a wind tunnel model and a remotely piloted vehicle presented in Figure 1.

An automated geometry modeling tool was developed in MATLAB to modify the GTM to have wing-mounted, distributed propulsors. The propulsive movements produced from distributing propulsors mounted along the wingspan would be used to optimize the spanwise lift distribution by modifying wing twist and shape. One flexible wing distributed propulsion concept was comprised of a single, wing-mounted turbogenerator on the inboard section of the wing that distributed electric power to four outboard electric propulsors for producing thrust.

Aerodynamic modeling

A NASA vortex lattice code, VORVIEW, was used to perform conceptual design studies on flexible wing distributed propulsion aircraft concepts. Potential flow theory, from which these methods are derived, assumes an incompressible, inviscid flow field. With Prandtl–Glauert corrections for compressibility, modifications to analyze thick airfoils and fusiforms to a reasonable accuracy, and the ability to calculate stability derivatives, the tool VORVIEW has proven very useful for performing preliminary aerodynamic analysis. Zero-lift drag, represented here as skin friction and pressure drag, is calculated for each configuration using direct numerical integration and added to the inviscid drag polar.

Distributed propulsion modeling

To complement the existing NPSS and WATE modeling tools for turbofan engines available through NASA Glenn, an analytical model for electric propulsor performance was developed. It was assumed that the propulsor consisted of two separate components:

1. a power-producing turbogenerator; and
2. a thrust-producing electric motor-driven fan unit.

By decoupling the propulsion elements, there appeared to be an opportunity to optimize each component for its specific function. A code was developed using MATLAB to size the propulsor units based on a requirement to match the sea-level static thrust of the conventional GTM aircraft. The associated fan thrust and weight were calculated assuming a fan pressure ratio at the takeoff condition.

Distributed propulsion modeling was performed assuming a hybrid electric distributed propulsion system architecture. Four designs were evaluated to determine which would produce minimum weight at the desired takeoff power assuming nominal scaling laws for conventional electric motors, generators, transformers, converters and motor controllers. The weight of electrical wiring and circuit protection systems was ignored in this study (Figure 2).

It was determined that the selection of a direct current (DC) motor for producing thrust allowed transformer weight and battery voltages to be minimized. This finding was consistent with technology trends that showed higher specific torque of the DC motor at a fixed rotations per minute compared with the alternating current (AC) motor.

Aero-propulsive structural modeling

Finite element methods were developed in MATLAB to model unsteady aerodynamics, structural mechanics and the aero-propulsive elastic coupling introduced through the interaction of the distributed propulsion and the flexible wing. A single-beam model was used to represent the wing structure due to its ability to model high aspect ratio wings. Mass and stiffness distributions were applied to the single beam at each node, each modeled with 6 df (Figure 3).

Aero-propulsive elastic design studies were conducted by varying the bending and torsional stiffness of the flexible wing, varying the placement of propulsors along the wing and

Figure 1 NASA GTM is used as the baseline aircraft model

(a) (b) (c)

Notes: (a) GTM remotely piloted vehicle; (b) experimental studies at NASA Langley; (c) GTM model with conventional wing design

Figure 2 Investigations of hybrid electric distributed propulsion system-level architectures

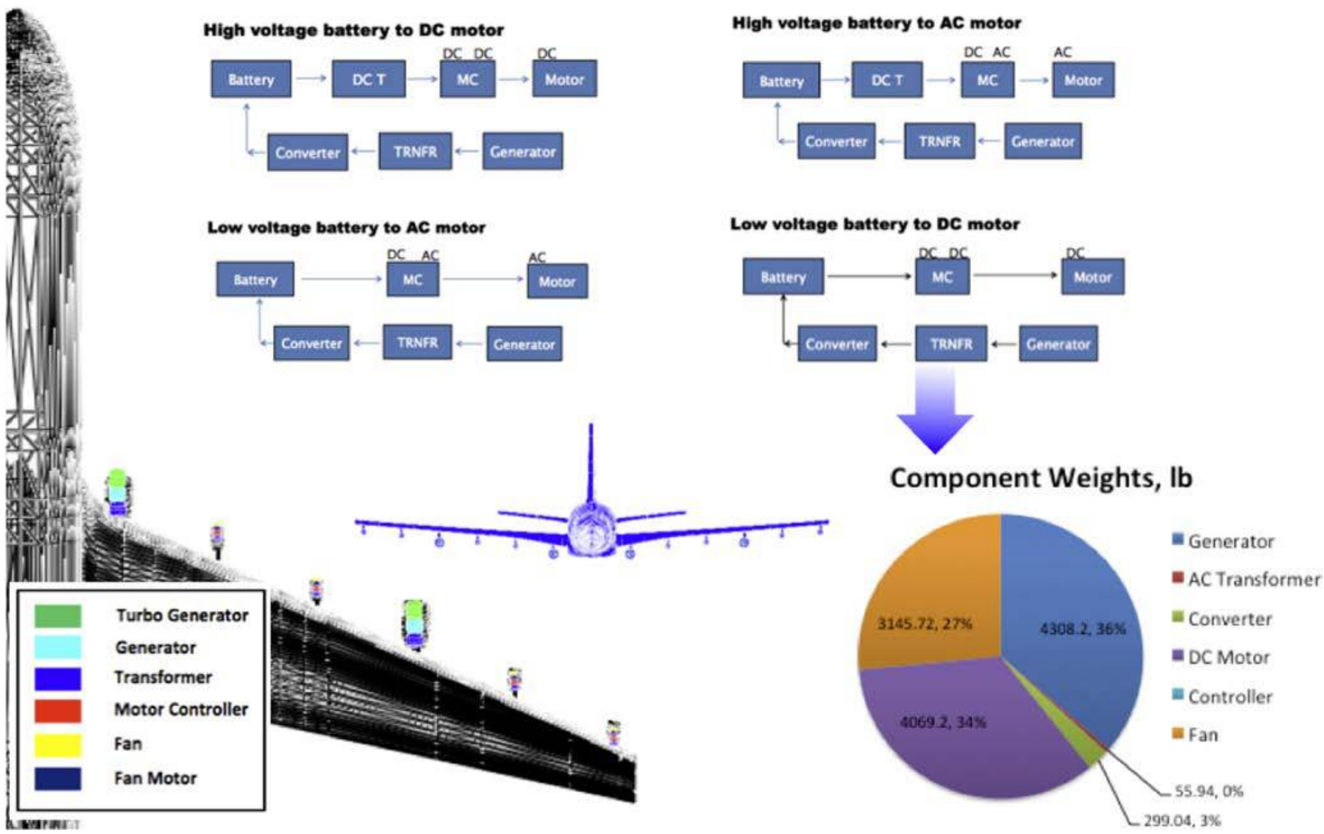
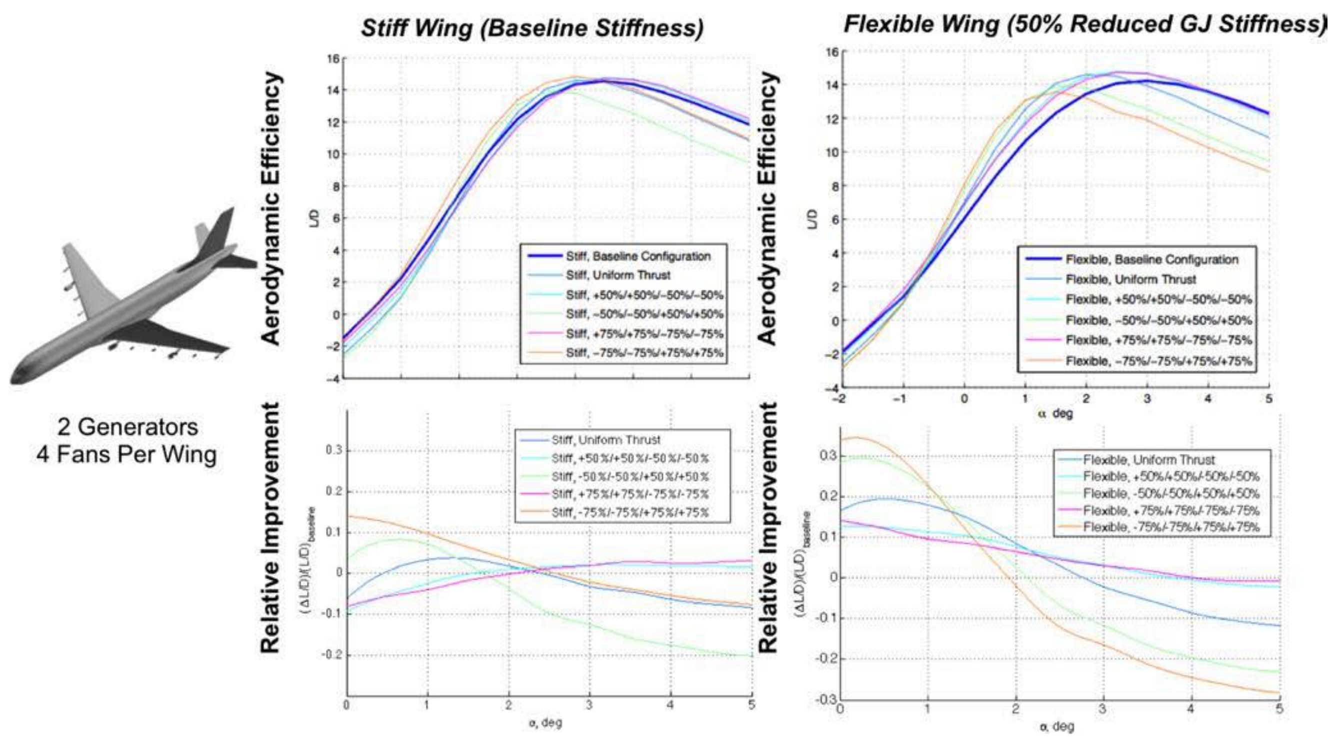


Figure 3 Aerodynamic efficiency measured as a function of wing stiffness and distribution of thrust along a wing



varying the distribution of thrust along the wing. The aeroelastic angle of attack was modified to account for the variation of spanwise lift as a function of thrust distribution:

$$\alpha_c = \alpha - \gamma - \Theta cos\Lambda - W_x sin\Lambda + \sum_{i=1}^{N} \frac{\partial \alpha_i}{\partial T_i} \partial T_i \quad (1)$$

where, the first two terms represent rigid contributions to angle of attack, the tertiary and quaternary terms represent contributions due to wing flexibility and the final term represents distributed propulsion wing shaping control.

Trajectory optimization

A typical mission for this transport aircraft consisted of a minimum fuel climb, a minimum fuel cruise and a continuous descent. For the climb, a singular arc was calculated using optimal control theory as the solution for minimum fuel to climb as a direct solution of the aircraft equations of motion. The singular arc is defined using specific excess thrust:

$$f(V,h) = F - V\frac{\partial F}{\partial V} - \frac{V^2}{g}\frac{\partial F}{\partial h} - \frac{FV}{cT}\left[\frac{\partial (cT)}{\partial V} - \frac{V}{g}\frac{\partial (cT)}{\partial h}\right] = 0,\ F = \frac{T - D}{W} \quad (2)$$

Two types of cruise were investigated:

1 constant Mach and constant altitude; and
2 constant Mach and constant angle of attack at maximum L/D.

The maximum weight of fuel was assumed to be 75,000 lbs/34,019 kg based on a maximum takeoff weight of 200,000 lbs/90,718 kg. The L/D improvement was evaluated relative to a baseline GTM with a range of 3,980 nmi/7,371 km (Figure 4).

The baseline GTM aircraft was shown to burn about 3,100 lbs/1,406 kg of fuel in climb. Wing shaping concepts at cruise showed potential to enable new optimal trajectories compared with a stiff wing aircraft by continuously varying the distribution of thrust to achieve maximum L/D at lower trim angles of attack (Figure 5).

Flutter analysis was performed for the single generator aircraft and showed no indication of aeroelastic instabilities. The flutter Mach number was well outside the flight envelope defined by the Federal Aviation Administration as 15 per cent margin above dive speed.

Conclusion

Wing shaping concepts using distributed propulsion show potential to achieve significant fuel burn reduction through the exploitation of coupled aero-propulsive elastic interactions. Preliminary results from trajectory optimization assumed candidate thrust distributions to show that a 4 per cent reduction in fuel burn could be achieved using wing shaping control with distributed propulsion on an unoptimized configuration. Aerodynamic penalties due to wing flexibility are compensated by tailoring the thrust distribution across the flight envelope to achieve optimal lift, minimum drag and reduced fuel burn. It was also determined that between 62 and 75 per cent of the vertical tail could be removed using differential thrust to create an effective "virtual rudder" for a given configuration.

Further work

Follow-on work will explore the potential to minimize structural weight and control effort using aero-structural tailoring and differential thrust. Further improvements to aerodynamic efficiency could result from boundary layer

Figure 4 Trajectory optimization for minimum fuel climb and maximum L/D cruise

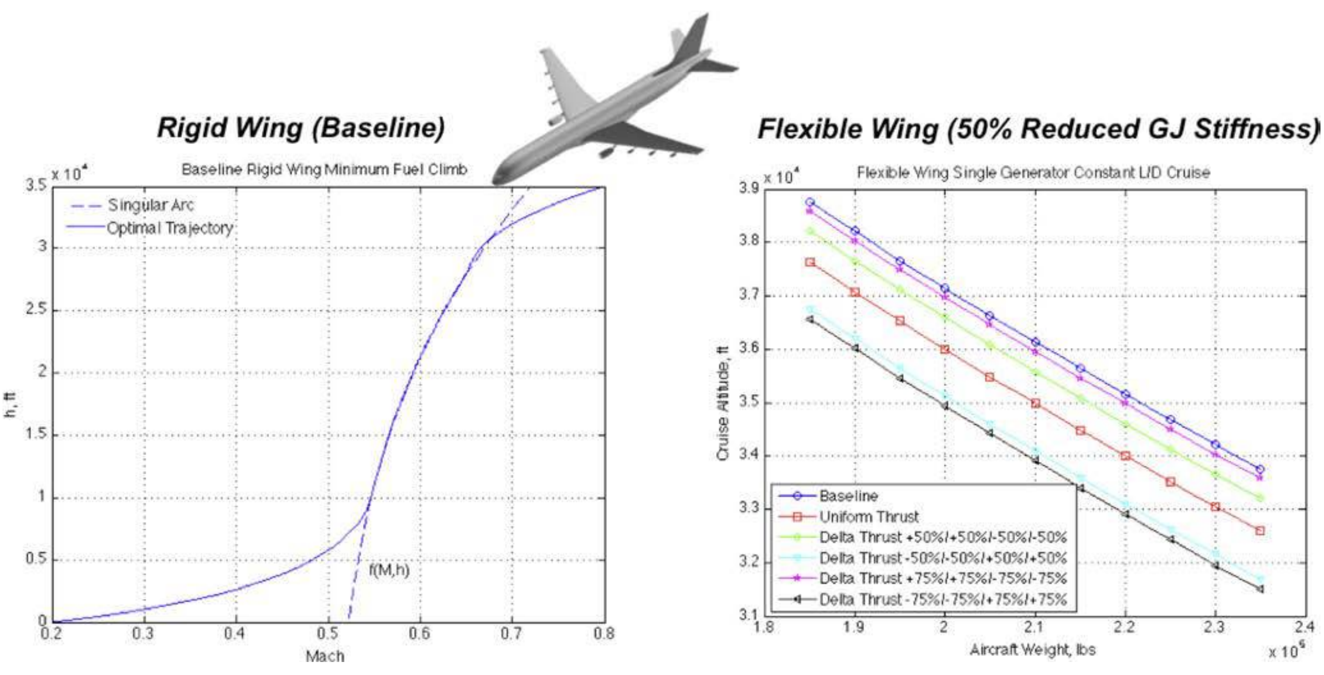
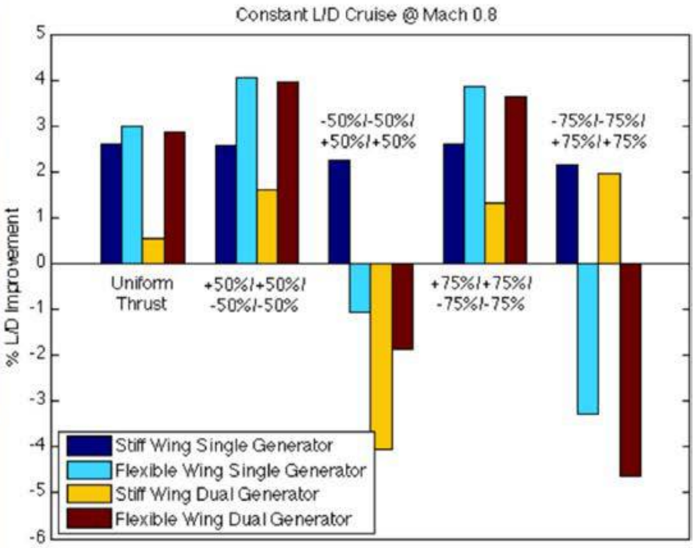


Figure 5 Trajectory optimization results for a mission profile comparing a stiff and flexible wing

Wing	Generator	Thrust	Range, mi	% L/D Increase
Stiff	Single	Baseline	3980	0.00
Stiff	Single	Uniform	4084	2.61
Stiff	Single	+50%/+50%/-50%/-50%	4082	2.57
Stiff	Single	-50%/-50%/+50%/+50%	4070	2.26
Stiff	Single	+75%/+75%/-75%/-75%	4083	2.59
Stiff	Single	-75%/-75%/+75%/+75%	4065	2.15
Flexible	Single	Baseline	3891	0.00
Flexible	Single	Uniform	4007	2.99
Flexible	Single	+50%/+50%/-50%/-50%	4048	4.04
Flexible	Single	-50%/-50%/+50%/+50%	3850	-1.05
Flexible	Single	+75%/+75%/-75%/-75%	4041	3.87
Flexible	Single	-75%/-75%/+75%/+75%	3763	-3.29
Stiff	Dual	Baseline	3980	0.00
Stiff	Dual	Uniform	4002	0.55
Stiff	Dual	+50%/+50%/-50%/-50%	4044	1.62
Stiff	Dual	-50%/-50%/+50%/+50%	3818	-4.07
Stiff	Dual	+75%/+75%/-75%/-75%	4032	1.32
Stiff	Dual	-75%/-75%/+75%/+75%	4058	1.97
Flexible	Dual	Baseline	3891	0.00
Flexible	Dual	Uniform	4002	2.85
Flexible	Dual	+50%/+50%/-50%/-50%	4044	3.95
Flexible	Dual	-50%/-50%/+50%/+50%	3818	-1.88
Flexible	Dual	+75%/+75%/-75%/-75%	4032	3.63
Flexible	Dual	-75%/-75%/+75%/+75%	3711	-4.62

Cruise Range for 50,000 lbs Fuel Burn



ingestion. This analysis will incorporate the use of medium to high-fidelity aerodynamic, propulsion and control design tools to enable adaptive aeroelastic wing shaping control.

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