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Morphing aircraft: The need for a new design philosophy

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ABSTRACT

This paper proposes a novel framework for classification of morphing technology based on its functionality, operation, and the structural layout. In addition, it highlights the limitations of the conventional design approach to exploit the benefits of the technology using representative examples and results.

1. Introduction

Concepts that enable radical shape changes to augment the flight performance or control aircraft were developed prior to the inaugural powered and controlled flight in 1903 [1]. Weisshaar et al. [2] state that the contributions of these pre 1903, and early variable geometry concepts, had little impact on the aviation community and its continuing development. The disappearance of these mechanisms in the early 1900's coincides with the increased requirement for greater structural rigidity due to the loads experienced (because of the greater demand for speed), which precluded the use of the flexible materials available during this era. Technological advancements have allowed renewed interest in mechanisms that enable significant configuration modifications, leading to a number of projects that have developed a number of morphing systems for actuating significant geometry modifications [3]. Example aircraft that deploy systems for significant planform changes include the F-14 and Tornado. These systems are used to adapt to varying flight phase or flight condition, for improved performance (either mission efficiency, controllability or manoeuvrability) through deploying 'rigid' body mechanisms. Recently, with the development of advanced materials, and wider application, or integration, of these more compliant materials to aircraft systems [4,5], there has been a revived interest in developing flexible mechanisms and structures that are capable of enabling significant planform changes through large deformations. With the concurrent development of novel structural arrangements (such as the FishBAC [6–9], compliant spar [10], zig-zag wingbox [11], the GNAT spar [12], hybrid hinge-less trailing edge concept developed at METU [13] and variable-stiffness camber morphing airfoil [14]), actuation methods, and multi-scale modelling and analysis techniques, has made it feasible to reinvestigate deploying these systems to achieve significant modifications to the aircraft geometry, and an opportunity for the successful integration of these systems onto full-scale aircraft. Barbarino et al. [3] present a more complete overview/review of aerospace morphing concepts and technologies that have been developed.

Morphing technology generally encompasses technologies that enable significant geometry modifications, although there exist several overlapping definitions of morphing in relation to aircraft. According to Weisshaar [2], morphing is a technology, or set of technologies, that allows air-vehicles to alter their characteristics to achieve improved flight performance and control authority, or to complete tasks that are not possible without this technology. The NATO RTO Technical Team on Morphing Vehicles suggested that morphing is the real-time adaptation to enable multi-point optimised performance [15]. A more detailed definition was provided by the DARPA Morphing Aircraft Structures (MAS) program. According to Seigler [16], the MAS program defines the morphing aircraft as a multi-role platform that changes its state substantially to adapt to changing mission environments, provides superior system capability not possible without reconfiguration, and uses a design that integrates innovative combinations of advanced materials, actuators, flow controllers, and mechanisms to achieve the state change.

Much of the literature on morphing to date includes structural concepts, morphing actuators and mechanisms, and some morphing systems analysis. Underlying the systems analysis, morphing structural concepts, actuators and mechanisms have generally been analysed as retrofitted systems to an already existing aircraft system [17,18], comparing the effect of retrofitting a morphing system relative to the performance of an equivalent classic system that delivers the same functionality. These investigations are largely

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Nomenclature

E_s	Young's modulus	GPa
E_{Eq}	Equivalent Young's modulus	GPa
ρ_s	Material density	kg/m^3
ρ_{Eq}	Equivalent material density	kg/m^3
K_x	Spanwise loading	N/m
α	Angle of attack	deg
β	Sideslip angle	deg
V_t	Relative wind velocity	m/s
p, q and r	Roll, pitch and yaw rate (rads/s) respectively	
ϕ, θ and ψ	Roll, pitch and yaw Euler orientation angles	deg
alt	Altitude	m
m	Mass	kg
I_{xx}	Rolling moment of inertia	kg m^2
I_{yy}	Pitching moment of inertia	kg m^2
I_{zz}	Yawing moment of inertia	kg m^2
I_{xz}	Cross-product of inertia in the X–Z plane	kg m^2
AR	Aspect ratio	
$l_{Stab.}/\bar{c}$	Ratio of tail moment arm (from wing leading edge to tail leading edge) to reference chord	
$l_{Fin}/\bar{c}$	Ratio of fin moment arm (from wing leading edge to fin leading edge) to reference chord	
$S_{Stab.}/S_{ref}$	Ratio of tail area to reference wing area	
S_{Fin}/S_{ref}	Ratio of fin area to reference wing area	
C_L or C_{Lift}	Non-dimensional lift coefficient	
C_D or C_{Drag}	Non-dimensional drag coefficient	
C_{D0}	Non-dimensional zero lift drag component	
C_l, C_m and C_n	Non-dimensional roll, pitch and yaw moment coefficient	
$HSTAB$	Horizontal stabiliser angle	deg

dependent on the aircraft system, and how capable the platform is able to accommodate a retrofitted morphing system. This does not necessarily demonstrate the potential performance benefits of morphing, as it is limited by the chosen platform's inherent performance. Furthermore, potential integration issues may decrease the feasibility of morphing due to excessive reduction in performance due to weight gain from the system, or structural issues with the integration itself. For concepts that modify the aerodynamic cross-section of a lifting wing, that are used to directly replicate an existing systems function, such as a compliant camber concept to replace a trailing edge flap, this may not be so difficult. However, concepts that modify the planform parameters can have a significant impact on the structural design. This may imply that the optimum geometry for a particular morphing concept within its morphing geometry space does not resemble a fixed wing designed for the same mission.

This paper shows that a retrofitted morphing concept does not yield the same solution as an aircraft system developed with morphing considered at the concept definition. This infers development of a design philosophy that includes morphing systems where fewer design constraints exist (from the conceptual design phase), such that morphing enlarges the design space to optimise the aircraft system.

In summary, the main research question the paper tries to answer is: Is it possible to exploit the full benefits of morphing technologies when they are retro-fitted to existing aircraft design rather than being considered early in the design process?

The research goals of this paper are to:

- Develop a novel framework for classification of morphing technology based on its functionality, operation, and the structural layout.
- Determine the limitations of the conventional design approach to exploit the benefits of the technology using representative examples and results.

2. Categorisation of morphing aircraft

Based on the definition of morphing outlined in Section 1, flaps, slats, and retractable landing gears are all forms of morphing that were adopted locally on conventional aircraft. These systems are categorised as 'Discrete Morphing'. Discrete morphing can be regarded as a mature technology, as these systems have been integrated onto airframes for almost 100 years. The primary reason for localised morphing is the need to improve operational performance, or control authority of the aircraft, without affecting the structural rigidity or integrity. Advances in materials and actuation systems facilitated the development of novel morphing structures, with directional properties that allows flexibility along one vector, whilst ensuring structural rigidity in another orthogonal direction. The benefits of localised morphing in terms of performance is limited largely by the planform, and can only optimise to the baseline planform, implying that discrete morphing may meet the continuous demand for more efficient and multi-mission aircraft.

Various categorisations of morphing have been proposed. Sofla et al. [19] and Barbarino et al. [3] categorise morphing based on geometric changes to commonly recognised parameters such as sweep angle, camber, twist, span and dihedral. These categorisations neglect conventional technologies such as flaps, slats and landing gears. Categorisations derived using this framework lack the generic description required to properly capture all forms of morphing, from classical discrete forms such as flaps and other trailing edge surfaces, to more contemporary compliant, or flexible structural concepts. The authors suggest a more generic categorisation of morphing system is required based on the functionality, operational envelope, and application. Flaps, slats, and retractable landing gears are integrated onto conventional aircraft typically for a singular function, only being deployed intermittently for a relatively short period of time during a mission flight phase. In addition, they are typically only applied locally in the airframe, and are not designed to carry the flight loads directly, but to transfer the load into the airframe's primary structural components (wing or fuselage). Only marginal performance improvements are expected, with the ability to meet future stringent requirements [3] questionable, due to the limited capacity for improvement in performance using these systems. Ultimately, an objective for future aircraft is to integrate so called 'Continuous Morphing' systems, where a single system can provide multiple functions, in a continuous fashion along a mission, where these systems are capable of carrying the various flight loads that the airframe is exposed to. Table 1 summarises the definitions and differences between 'Discrete' and 'Continuous' Morphing.

Continuous morphing can be observed in nature through bird' wings, which can morph to adapt to multiple missions, such as loiter and strike, with varying functionality and requirements from control to flight performance. Examples of both 'Discrete' and 'Continuous' Morphing are shown in Fig. 1.

3. Morphing aircraft design

Most of today's aircraft are designed according to Cayley's design paradigm [1] which separates the functions required for sustained flight [20,21,1], mainly the lifting and propulsive systems.