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The Zigzag wingbox for a span morphing wing

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ABSTRACT

This paper presents the Zigzag wingbox concept that allows the wing span to be varied by 44% (22% extension and 22% retraction). The Zigzag wingbox consists of a rigid part and a morphing part. The rigid part is a semi-monocoque construction that houses the fuel tank and transfers the aerodynamic loads from the morphing part to the fuselage. The morphing part consists of various morphing partitions where in each partition there are two spars each consisting of two beams hinged together. Each morphing partition is covered by flexible skin and is bounded by two ribs through which the spars are connected. The ribs transfer the loads between the spars of adjacent morphing partitions and serves as the main structure to which the flexible skins are to be attached. The Zigzag wingbox concept is then incorporated in the rectangular wing of a medium altitude long endurance (MALE) UAV to enhance its operational performance and provide roll control. Equivalent modelling and preliminary sizing of the concept are performed to assess its feasibility and quantify its potential benefits.

1. Introduction

Continuous demands to enhance flight performance and control authority have focused the interest of aircraft designers on span morphing. Wings with large spans have good range and fuel efficiency, but lack manoeuvrability and have relatively low cruise speeds. By contrast, aircraft with low aspect ratio wings can fly faster and become more manoeuvrable, but show poor aerodynamic efficiency [14]. A variable span wing can potentially integrate into a single aircraft the advantages of both designs, making this emerging technology especially attractive for military UAVs. Increasing the wingspan, increases the aspect ratio and wing area, and decreases the spanwise lift distribution for the same lift. Thus, the drag of the wing could be decreased, and consequently, the range or endurance of the vehicle increase. Unfortunately, the wing-root bending moment can increase considerably due to the larger span. Thus the aerodynamic, structural, aeroelastic, and control characteristics of the vehicle should be investigated in the design of variable-span morphing wings. Most span morphing concepts are based on a telescopic mechanism, following the ideas of Ivan Makhonine, a Russian expatriate, where the wing outer panel telescoped inside the inner panel to enable span and wing area changes. The MAK-10 was the first design with a telescopic wing and it first flew in 1931. The mechanism was powered pneumatically and enabled span increases up to 62% (from 13 to 21 m) and area increases up to 57% (from 21 to 33 m^2) [22]. Blondeau et al. [6] designed and fabricated a three segmented telescopic wing for a UAV. Hollow fiberglass shells were used to preserve the spanwise aerofoil geometry and ensure compact storage and deployment of the telescopic wing. To reduce the weight, they replaced the wing spars with inflatable actuators that could support the aerodynamic loads on the wing (in excess of 73 kg/m^2). Their telescopic spar design consisted of three concentric circular aluminium tubes of decreasing diameter and increasing length, connected by ceramic linear bearings, and deployed and retracted using input pressures of 345–483 kPa (50–70 psi). The wing could undergo a 114% change in the aspect ratio, while supporting aerodynamic loads.

Blondeau et al. [7] adopted two identical telescopic spars instead of one, mechanically coupled by the ribs, to prevent wing twist and fluttering. The new prototype could undergo a 230% change in aspect ratio, and seam heights were reduced giving less parasitic drag. In its fully deployed condition the telescopic wing could achieve lift-to-drag ratios as high as 16, which was similar to its solid foam-core wing counterpart. The most dramatic morphing wing involving span change that has been realised as a wind tunnel prototype is the Agile Hunter by Lockheed Martin [9,11,13]. Funded by DARPA within the MAS program, the prototype was based on a military UAV capable of folding the inner sections of the wing near to the fuselage, to reduce the surface area and drag

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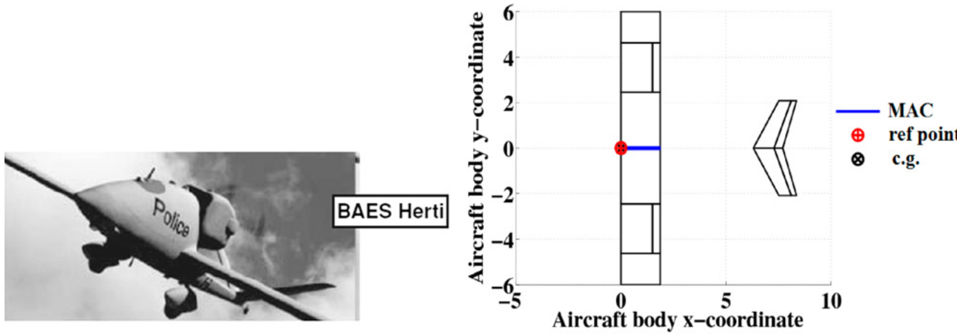

a) BAE Systems Herti UAV   b) The MALE UAV in Tornado

Fig. 1. The MALE UAV considered.

during transonic flight at low altitude (also called a Z-wing). The major challenge was the realisation of suitable hinges that connect the two wing portions; the hinges have to sustain the aerodynamic loads but offer a smooth, continuous aerodynamic surface. Several materials were considered, including silicone-based and Shape Memory Polymer skins. Wind tunnel tests at Mach 0.6 showed a morphing capability from 0° to 130° over 65 s with a controllable, reliable and precise actuation. Bae et al. [4] performed both static aerodynamic and aeroelastic studies on the wing of a long-range cruise missile and highlighted some of the benefits and challenges associated with the design of a morphing wing capable of span change. The total drag decreased by approximately 25%, and the range increased by approximately 30%. The aeroelastic analysis showed that the flexibility of the morphing wing structure increased as the wingspan increased. At a given flight condition, the deformation from the aerodynamic loads was much larger than that of the conventional wing. Static aeroelastic considerations that a variable-span wing requires increased bending stiffness because the bending deformation is more significant than twist.

Asymmetrical span morphing can be used for roll control. Ajaj et al. [1] investigated the use of asymmetric span morphing to replace conventional ailerons and provide roll control for a medium altitude long endurance (MALE) UAV. In addition, they optimised the rolling strategy to minimise drag for a steady roll manoeuvre.

Seigler et al. [19] investigated asymmetrical span extension for increased manoeuvrability of bank-to-turn cruise missiles. By formulating a full nonlinear model of the missile, due to the shift of the missile centre of mass and the dependence of the rolling moment on the angle of attack, they showed that the control authority can be significantly larger when compared to conventional tail surface control. Improved manoeuvrability, however, is highly dependent upon the angle of attack, linear actuation speed, and extension length. Moreover, as the mass of the extending wings becomes large relative to the missile body, the rigid body dynamics can become increasingly complex and a nonlinear control law was formulated to control the roll, angle of attack, and side slip angle dynamics in accordance with bank-to-turn guidance. The control method proved to be adept in tracking commanded inputs while effectively eliminating sideslip. Seigler et al. [20] studied the modelling and flight control of vehicles with large-scale planform changes. The equations of atmospheric flight were derived in a general form, methods to integrate the aerodynamic forces examined, and various approaches and methods of flight control distinguished. A more extensive review on span morphing technology (applications and concepts) for both fixed-wing and rotary-wing aircraft is given in Barbarino et al. [5].

The main objective of this paper is to develop a structural concept that allows the wing span to be varied to provide roll control and enhance the operational performance of a MALE UAV. Equivalent modelling of the concept is performed using Euler–Bernoulli beam theory and thin-walled structures. Then preliminary sizing, weight estimation, and sensitivity study are conducted to determine the feasibility and highlight the potential benefits and possible drawbacks. The flexible skin and actuation system to be used are also addressed.

2. Aerodynamics

The Tornado Vortex Lattice Method (VLM) was used for aerodynamic predictions. Tornado is a linear aerodynamics code, and discounts wing thickness and viscous effects [15]. These limitations imply that Tornado can only be used for angles of attack up to 8–10° for slender wings. Linear aerodynamic theory is still nevertheless very useful as most aircraft typically operate within the linear region (operating lift coefficients at reference speeds) in cruise/endurance, as well as both take-off and landing phases. These are the flight stages in which most of this research and analysis has been undertaken.

In Tornado, usually one half of the wing is built and then mirrored with respect to the centerline of the aircraft to generate the entire wing. In order to investigate roll control using span morphing, each half of the wing is built separately to allow the asymmetric change in span. Typically the wing is defined from the root to the tip in Tornado for the symmetric case. However for the asymmetric case, one half of the wing is defined from root to tip and the other half is defined from tip to root. As the wing semi-span starts to increase the size of the spanwise elements start to increase resulting in a coarser aerodynamic mesh. A convergence study was performed to determine the size of the aerodynamic mesh required to generate accurate and robust results. Five chordwise elements and 20 spanwise elements are sufficient to provide robust prediction with a relative error of 0.05%. A linear distribution for the spanwise and chordwise panels was adopted.

A MALE UAV similar to the BAE Systems Herti UAV [3] (shown in Fig. 1a) was selected for this study. The UAV is modelled in Tornado VLM as shown in Fig. 1b and has a maximum lift-to-drag ratio of about 20 and a maximum endurance capability of about 18 hours. Fig. 1b also shows the position of the Mean Aerodynamic Chord (MAC). A representative flight profile, shown in Fig. 2, was assumed in this analysis. The UAV takes-off with a weight of 800 kg and it cruises and loiters for about 18 hours with a speed of 50 m/s (M0.16) at 6100 m (20,000 ft) and then it descends and lands. The design parameters of the vehicle are given in Table 1.

3. Benefits of span morphing

Ajaj et al. [2] investigated the use of asymmetric span morphing to provide roll control and replace conventional ailerons. In addition, they assessed the potential benefits of symmetric span