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FEASIBILITY ANALYSIS OF SPAN EXTENSION OF MORPHING HALE UAV WING

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Abstract

This paper explores the benefits of providing telescopic span morphing in HALE UAV for extending its endurance, while retaining its performance in other flight segments such as climb rate, take-off/landing and so on.

Existing methodology for initial sizing and constraint analysis has been used with Global Hawk RQ4-A as the baseline aircraft and a modified Global Hawk with requirement for additional endurance is investigated by morphing due to span extension. The benefits of morphing of HALE UAV for extending its endurance are reported.

The telescopic span extensions planned for the Global Hawk lead to an increase in lift-to-drag ratio of the aircraft in morphed configuration. Three morphing configurations are defined in relation to the base configuration in terms of increasing wingspan as a 'morphing coefficient'. Two penalties associated with telescopic span morphing are taken into account – weight of the morphing mechanism and fuel volume lost.

The effects described above i.e. increased lift-to-drag ratio, reduced available fuel volume and increases empty weight; are factored in to estimate the new weight of the aircraft and the endurance benefit is evaluated.

It is found that for the same mission profile, as morphing coefficient increases, endurance benefit increases and then decreases. This indicates presence of a limit, beyond which the morphing has no endurance benefit.

Effects of morphing on controllability and aeroelasticity are not in the scope of this study.

1 Introduction

High Altitude Long Endurance (HALE) aircraft are a peculiar category of aircraft. While conventional transport aircraft fly at the upper reaches of the troposphere i.e.: at an altitude of 10 km, a HALE aircraft would operate in the stratosphere at altitudes in excess of 15 km, as seen in **Table 1**.

Table 1. Comparison of service ceilings of aircraft categories

Class	**Represent-ative Aircraft**	**Service Ceiling (km)**	**Endurance without ATA refuelling (hrs)**
Jet airliner	Boeing 787-8	13	~ 18
Fighter jet	Sukhoi-30MKI	15	~ 3.75
HALE aircraft	Global Hawk RQ-4A	18.3	~ 32

The key mission feature of a HALE aircraft (see specifications in Table 2) is that it flies out of the reach of interception and adverse tropospheric weather conditions, and also doesn't interfere with commercial air traffic. In addition, surveillance payloads mounted on HALE aircraft have the advantage of altitude. Being situated at a greater height, payloads such as Synthetic Aperture RADAR (SAR) and electro-optic sensors are able to cover larger swathes of land in a single frame of data, without compromising narrow angle field-of-view. As a result of this, the mission roles that have been contrived for HALE Unmanned Aerial Vehicles (UAV) are of long duration.

One of the objectives of design of HALE aircraft has been to maximise the on-station endurance. Several methods have been adopted for this, and the focus has largely been on improved propulsion, including non-conventional propulsions systems such as hydrogen power, solar power and hybrid systems [4][5], [6] and even air-to-air refuelling [7].

Table 2. Specification of RQ4-A

Parameter	Value	Ref.
Payload	907 kg	[1]
Loiter Altitude	16.8 km	[2]
Cruise Mach Number	0.60	[2]
Cruise SFC	0.6 /hr	[2]
Gross Still Air Range	1200 nm	[1]
Endurance	24 hrs	[1]
Wing Airfoil Section	LRN 1015	[3]
Wing Aspect Ratio	25	[3]
C_L in Loiter	1.0	[3]

One of the methods of boosting endurance that has been briefly explored is to improve the lift-to-drag ratio in loiter using telescopic span morphing [8],[9], [10]. Most studies of this nature have been on electric UAVs. In the case of larger HALE UAVs having wing fuel tanks [11], telescopic span extension has the added penalty that it leads to a loss of fuel tank capacity. Thus, a feasibility-check needs to be carried out before applying telescopic span extension to HALE UAVs.

The aerodynamic design of a HALE aircraft is a trade-off between conflicting requirements, and the final configuration is ultimately chosen based on a mission-critical segment. The chosen configuration would cater to the needs of a performance related mission segment such as climb or turn rate, but might, at the same time, result in sub-optimal performance in other mission segments, such as loiter. Morphing may be carried out to improve the endurance in this phase while still retaining the desired performance parameters in the other phases.

2 Methodology

In this study, the RQ4-A Global Hawk is taken as a base-line HALE UAV design. Initial sizing methodology is implemented as presented in standard texts in aircraft design [3] [12]. The baseline aircraft wing is then morphed using telescopic span extensions. The advantage gained from morphing is measured in terms of extension of endurance in the mission loiter segment. In other words, increase in on-station loiter is seen as the quantifiable benefit of morphing.

2.1 Initial Sizing Methodology of representative HALE UAV – Calculation and Validation

Table 2 lists Global Hawk design data obtained from various sources.

Fuel weight fraction estimation is carried out using a representative mission profile (Fig. 1) for a HALE UAV mission used from [13].

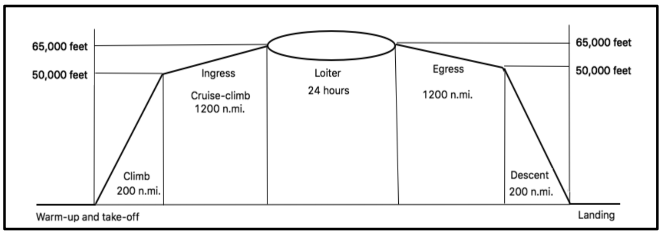

Fig. 1. Representative RQ4-A Mission Profile

The cruise and endurance segment weight fractions are calculated using Breguet equations. Estimation of lift to drag ratio for use in these equations is carried out by the methods presented in [3].

Table 3 shows the parameters used for estimation of L/D in cruise and loiter. Total drag is estimated by the following equation i.e.: by summing up the zero lift drag coefficients of the wing, body and miscellaneous drag items with the induced drag due to lift as per equation 1 from [3].

$$C_D = C_{D_0 wing} + C_{D_0 body} + \Delta C_{D_0} + C_{D_L} \qquad (1)$$

The wing contribution is estimated using the equation 2 from [3]. Calculated values are shown in

.

$$C_{D_0 wing} = C_f \left[1 + 1.2\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4\right] R \left(\frac{S_{wet}}{S_{ref}}\right) \qquad (2)$$

Table 3. Values of Parameters in Estimation of Wing C_{D0}

Parameter	Symbol	Value
Maximum thickness ratio for LRN 1015	t/c	0.16
Roughness Height Value - Smooth Matte Paint (in)	k	0.00025
Mean aerodynamic chord / Roughness Height	l/k	3.15×10^5
Cut-off Reynolds number	Re_l	2.10×10^6
Wing Reynolds number	Re_e	4.43×10^6
Flat Plate Skin Friction Coefficient	C_f	0.0031
Lifting-surface correlation factor	R	1.15
Wetted surface area (m^2)	S_{wet}	91.40
Wetted area ratio	$\frac{S_{wet}}{S_{ref}}$	1.82
Wing-zero-lift-drag coefficient	$C_{D_{0\,win}}$	0.00815

Similarly, the body zero-lift drag coefficient [3] is estimated from equation 3 and results are presented in Table 4.

$$C_{D_{0\,body}} = C_f\left[1+\left(\frac{60}{(l_B/d)^3}\right)+0.0025\ (l_B/d)\right]\left(\frac{S_S}{S_B}\right) \quad (3)$$

Table 4. Values of Parameters in Estimation of Body Zero-Lift Drag Coefficient

Parameter	Symbol	Value
Body fineness ratio	l_B/d	9.953
Max cross sectional area of body (m^2)	S_B	1.646
Wetted area of body surface (m^2)	S_S	65.542
Wing zero-lift drag coefficient (with reference to wing reference area)	$C_{D_{0\,body}}$	0.00439

Zero lift drag coefficient due to miscellaneous drag items are estimated using methods from [3], [12] and the results are expressed in **Fig. 2**.

Thus, the total zero-lift drag coefficient is found to be 0.01423. The lift induced drag for cruise and loiter segments is estimated from equation 4.

$$C_{D_L} = \frac{1}{\pi\, e\, AR} {C_L}^2 \quad (4)$$

where span efficiency factor is given by the following equation 5 [14].

$$e = \frac{2}{2 - AR\sqrt{4 + AR^2}} \quad (5)$$

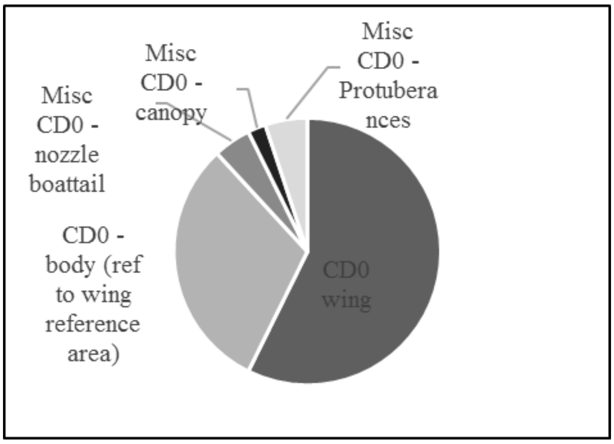

Fig. 2. Estimation of C_{D0}

Thus, the lift to drag ratios for cruise and loiter segments are estimated and the values are are 35.840 and 36.397 respectively.

Fuel weight fraction for this mission is calculated, using the above data and methods from [12]. After having accounted for 10 % reserve fuel, the fuel weight fraction is estimated as 0.422.

Using thus-estimated value of fuel weight fraction, empty weight fraction and actual payload, the Maximum Take-Off Weight (MTOW) of the UAV is determined. It is found that the calculated value is reliably close to the actual value of MTOW of the RQ4-A Global Hawk [15] within an error margin of 1.7%. This validates the methodology and numbers used for initial sizing of the RQ4-A Global Hawk.

3 Telescopic span morphing of baseline aircraft

3.1 Constraint Analysis

Constraint Analysis is a procedure that allows a designer to arrive at the values of W/S and T/W that meet all user-specified and regulatory constraints. A constraint analysis for RQ4-A was carried out to meet the mission requirements viz., take-off distance, climb rate, cruise speed, stall speed, sustained and instantaneous turn rates, to arrive at the optimal wing loading and thrust loading values of 240 kg/m^2 and 0.29, respectively, as shown in Fig. 3.

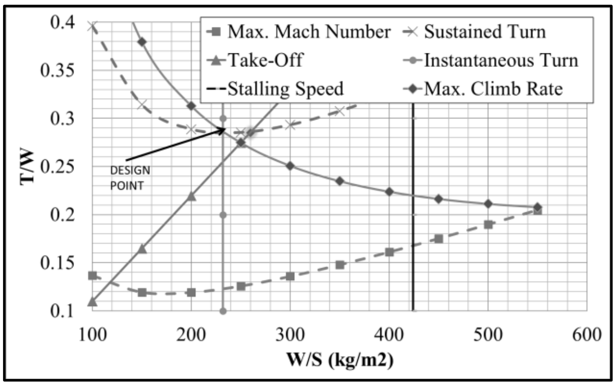

Fig. 3. Constraint Analysis for RQ4-A Global Hawk

Fig. 3 shows that maximum climb rate and instantaneous turn rate are the design-drivers for the RQ4-A. There is an upper bound on the wing planform area. However, for greater endurance, it is desirable to have as large an aspect ratio, and as low a wing-loading as possible. This brings us to the requirement to have span extension to increase endurance.

3.2 Stretched Global Hawk

A possibility of having a HALE UAV design with endurance of three hours more than the baseline design is considered. This "stretched" Global Hawk would have the same empty weight fraction and aerodynamic parameters as before.

On performing the same initial sizing calculation using the methodology explained above, it is found that the MTOW of the new configuration would be much larger and consequently, in order to meet the same performance parameters as laid down in the constraint analysis, the wing area needs to be modified. The configuration of the stretched Global Hawk would have specifications as shown in Table 5.

Table 5. Parameters of Stretched Global Hawk

Parameter	Baseline	Stretched
Maximum Take-off Weight (kg)	16100	12134
Endurance (hrs)	27	24
New reference area (m^2)	64.14	52.2
New wingspan (m)	43.5	35.4
New thrust (kg)	4605	3470

3.3 Morphing Mechanism

3.3.1 Description

The telescopic span extensions planned for the RQ4-A Global Hawk are graphite – epoxy fibre reinforced composite wing sections. The structural construction techniques are assumed to be identical to those used in the main wing-box itself. Weights of the extensions are considered based on experience of working with CFRP wing structures. As an initial guess, a conventional quasi-isotropic layup of 6 mm thickness is considered to estimate the total weight of the telescopic wing structure. There are no control surfaces on the wingtip extensions. Effects of morphing on controllability and aero-elasticity are not considered in the scope of this study.

The actuation mechanism of the telescopic spar is hydraulic. Standard differential industrial hydraulic cylinders with round mounting flanges are selected based on the actuated load [16]. Three sizes of hydraulic actuators are selected based on the available stroke length. Accordingly, three morphed "Global Hawk" aircraft are defined with 4 m, 6 m and 9 m wingspan extension. The degree of morphing is quantified by a "morphing coefficient" (µ) of 0 to 100, defined as a fraction of the maximum planned span extension, with 0 being the baseline aircraft and 100 being the longest morphed span. Thus, three morphed configurations are defined with MC of 35, 52 and 100.

3.3.2 Calculations

The weight and mounting configuration of the actuators is obtained from standard catalogues [17]. From this, the empty weight fraction of the three aircraft is updated as shown in Fig. 4.

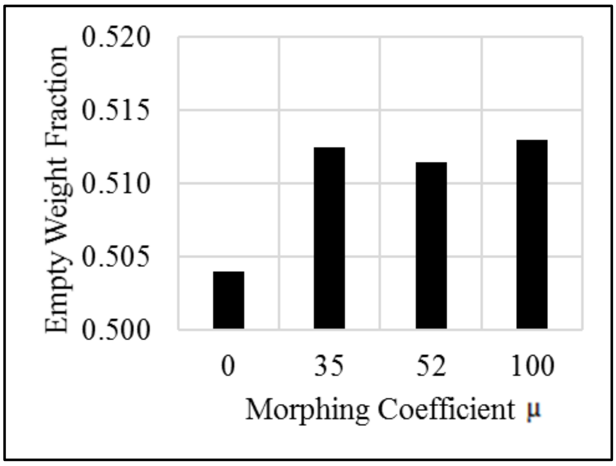

Fig. 4. Morphed Aircraft Empty Weight Fractions

For each of the three chosen aircraft, aerodynamic lift and drag estimation is carried out by the procedure described earlier.

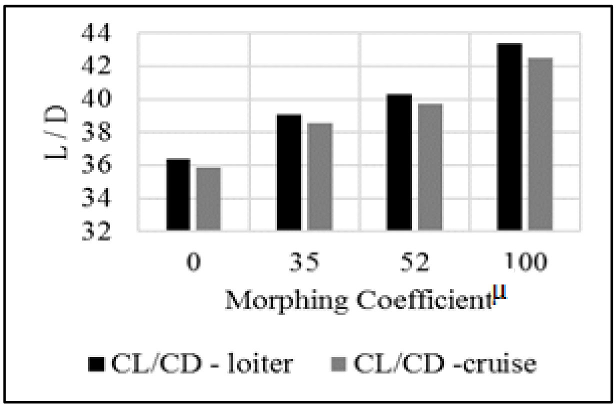

Fig. 5. Morphed Aircraft Lift-to-Drag Ratios

As expected, the calculations show that span extension leads to an increase in the ratio of wetted surface area to reference area (S_{wet}/S_{ref}) despite an increase in S_{ref} and ultimately, a net decrease in C_{D0}. This leads to up to an 18% rise in lift-to-drag ratio as shown in Fig. 5.

In addition to this, the fuel volume lost because of the morphing mechanism housed in the wing is calculated. It is observed that ~ 25% of the original fuel mass could be lost due to this as observed from Fig. 6.

Accounting for all three effects described above i.e. reduced lift-to-drag ratio, higher empty weight and lower available fuel volume, the new maximum take-off weight of the aircraft is evaluated by the same procedure as before using the same basic mission profile. Thus, the net fuel consumption is calculated, from which excess endurance is calculated as shown in Fig. 7.

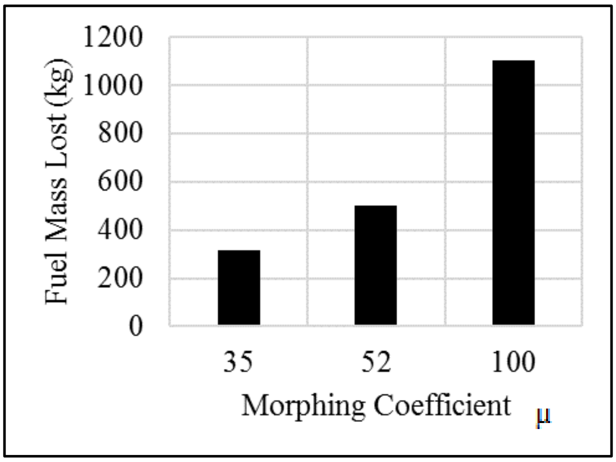

Fig. 6. Fuel Mass Lost due to Morphing Mechanism

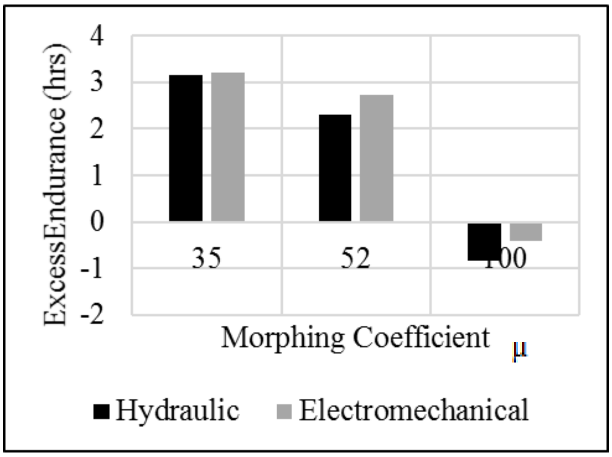

Fig. 7. Excess Endurance Available - Morphed Aircraft

4 Results and Conclusion

In order to obtain a slight increase in endurance without affecting the performance of the aircraft in other segments such as climb, morphing gives an advantage, and is a better option to consider than resizing the aircraft entirely.
However, while implementing morphing, for the same mission profile, as morphing coefficient μ increases, fuel saving initially increases and then starts decreasing, ultimately arriving at a limit, beyond which the aircraft actually consumes more fuel than allowed for the original mission. Thus, the study gives an estimate of the extent to which wing morphing using telescopic span

extension devices is actually feasible for HALE UAVs.

References

[1] *Global Hawk Brochure.* Northrop Grumman, 2006.

[2] Halliwell I. An Improved Engine for a High Altitude Long Endurance Unmanned Air Vehicle - Request for Proposal. *Joint AIAA Foundation/ASME.IGTI Student Design Competition*, 2012.

[3] Nicolai L M, Carichner G E. *Fundamentals of Aircraft and Airship Design - Volume I*, 1st Edition, American Institute of Aeronautics and Astronautics, 2010.

[4] *Global Observer Data Sheet.* Aerovironment Inc., 2009

[5] Meyer J, du Plessis F, Clarke W. Design Considerations for Long Endurance Unmanned Aerial Vehicles, *Aerial Vehicles*, Thanh Mung Lam (Ed.), InTech, 2009.

[6] Lieh J, Spahr E, Behbahani A, Hoying J. Design of Hybrid Propulsion Systems for Unmanned Aerial Vehicles. *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, San Diego, paper number 6146, 2011.

[7] *RQ-4 NASA Global Hawk*. Northrop Grumman Aerospace Systems, 2013.

[8] Barbarino S, Bilgen O, Ajaj R M, Friswell M I, Inman D J. A Review of Morphing Aircraft, *Journal of Intelligent Materials Systems and Structures*, Vol. 22, paper number 9, pp. 823–877, 2011.

[9] Min Z, Kien V K, Richard L J Y. Aircraft morphing wing concepts with radical geometry change, *The IES journal. Part A Civil & structural engineering*, Vol. 3, paper number 3, pp. 188–195, 2010.

[10] Santos P, Sousa J, Gamboa P. Variable-span wing development for improved flight performance, *Journal of Intelligent Materials Systems and Structures*, pp. 1–18, 2015.

[11] Liu X D, Li S L, Tang Y. Fuel System Configuration and Restructuring of MALE and HALE UAV, *Applied Mechanics and Materials*, Vol. 779, pp. 268–276, 2015.

[12] Raymer D P. *Aircraft Design: A Conceptual Approach*. 5th edition, American Institute of Aeronautics and Astronautics, 2012.

[13] Lamb G S, Stone T G, Barton Jr H H, Downer L A, Hawley R E. *SECTION 3 - OPERATIONS - Endurance UAV CONOPS [Concept of Operations] Air Combat Command*. Version 2, USAF, 1996. [Online] Available: http://fas.org/irp/doddir/usaf/conops_uav/part03.htm. [Accessed: 01-Jul-2016].

[14] Brandt S A, Stiles R J, Bertin J J, Whitford R. *Introduction to Aeronautics: A Design Perspective.* Third Edition, 3rd edition, American Institute of Aeronautics and Astronautics, 2015.

[15] Martin L C. *Engineering Technical Letter (ETL) 09-1: Airfield Planning and Design Criteria for Unmanned Aircraft Systems (UAS),* AFCESA, 2009.

[16] Fincham J, Beaverstock C S, Coles A B, Parsons L L, Ajaj R M, Friswell M I. *Proceedings of the Royal Aeronautical Society Advanced Aero Concepts Design and Operations Conference*, Bristol, 2014.

[17] *Hydraulic cylinder Types CDH1 / CGH1*, Rexroth Bosch Group, 2003.

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