

OPTIMISING MISSION PERFORMANCE FOR A MORPHING MAVC. S. Beaverstock^{*}R. M. Ajaj[†] and M. I. Friswell[‡]Swansea University
Swansea, United KingdomR. De Breuker[§] and N. P. M. Werter[¶]Delft University of Technology
Delft, The Netherlands**ABSTRACT**

Morphing concepts integrate mechanisms capable of actuating significant planform or configuration changes. Articulation can be achieved through integration of a mechanism composed of rigid structural members, or in a more contemporary approach, by integrating compliant members to accommodate large deflections or changes in geometry. It is supposed that with large modifications to the wing geometry, mission performance can be improved over a range of flight conditions. Alternatively, the flight envelope could be expanded to complete multiple mission specifications, which potentially require significant geometry modifications to operate. Estimation of the effect on the mission performance is essential whether morphing improves overall mission capability, or if multiple mission requirements are the objective. This paper proposes an architecture for a low-fidelity, conceptual software framework to be used in assessment of Unmanned Air Vehicles (UAVs) that implement morphing wing technology. The paper also includes example results of a ~ 25 kg UAV using this tool. The mission includes a high speed cruise and a loiter phase. Span and twist morphing are modelled to investigate the effect of introducing these on the aerodynamic efficiency (range and endurance). The results show that using span morphing, the optimum speed for aerodynamic efficiency increases with span retraction. However, ultimately the results show that maximum aerodynamic efficiency with morphing is lower than that when operating at full span and equivalent speed. Introduction of a linear twist improved the optimum efficiency, where only marginal improvements are observed if allowed to vary. However, the results show a reduction in root bending moment can be achieved through both span and twist morphing. In the case of twist without significant loss in aerodynamic efficiency. Sensitivity to variations in mass and longitudinal Centre of Gravity (CoG) position on the aerodynamic efficiency are also included. Other results are included that show excessive control surface deflections are required to trim the UAV longitudinally over the speed range of interest, which suggests an insufficient tail volume coefficient, necessitating re-design of the empennage. These results primarily show that both span and twist morphing alone do not provide significant aerodynamic benefits, but do reduce root bending moments which could potentially reduce weight and increase in mission performance.

^{*}Research Officer, Email: c.s.beaverstock@swansea.ac.uk

[†]Lecturer, Email: R.M.Ajaj@swansea.ac.uk

[‡]Professor of Aerospace Structures, Email: m.i.friswell@swansea.ac.uk

[§]Assistant Professor, Email: R.deBreuker@tudelft.nl

[¶]Research Assistant/ PhD Student, Email: N.P.M.Werter@tudelft.nl

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Nomenclature

α	Angle of attack (deg)
V_t	Relative wind velocity (m/s)
q	Pitch rate (rads/s)
θ	Pitch angle (deg)
alt	Altitude (m)
m	Mass (kg)
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

INTRODUCTION

Integration of movable surfaces that modify the aircraft aerodynamic boundary are necessary to provide control forces and moments across the flight envelope. The original system employed to control aircraft integrated a system of wires and pulleys to modify the plan-form twist, or camber, applied at span-wise wing cross-sections, referred to as 'wing warping' [5]. With increasing speed demands on aircraft, stiffer airframes were required to support the increased load. As such, discrete surfaces were adopted in favour of compliant warping systems, where actuated surfaces are employed rather than a compliant structure. This essentially extends the application of Cayley's design philosophy. The principle was to separate the lifting system from the propulsive system to enable pseudo-independent development, where development of the flying control system can be performed as a separate design task to the planform geometry of the wing, which is a primary component that determines the performance. Furthermore, with increasingly demanding flight phase requirements (for example performance constraints for climbing and decent, take-off and landing field length restrictions), deployable surfaces that modify the wing configuration were integrated to augment the flight mechanics during these phases. Essentially, decoupling the systems was necessary to model and understand the task, to further enable efficient and effective design. However as Campanile [4] notes this limits the performance potential of the aircraft system, by limiting the design space, erecting arbitrary, albeit logical, boundaries to the analysis.

Classical design development generally focuses on a limited set of critical flight conditions for sizing, where the sizing for aerodynamic efficiency is generally determined at the cruise condition, with compromises to this geometry to accommodate constraints at other flight phases. This inhibits implementation of the optimum geometry, where generally the optimum geometry for each flight phase varies, rendering the final design sub-optimal. Variable geometry concepts provide an option with the potential to capture the optimum at each flight phase. This paper presents an example of a UAV equipped with a morphing wing, investigating the effect of modifying the span and twist on the UAV performance.

A BRIEF BACKGROUND

Contemporary design considers morphing as an activity whereby actuated mechanisms or compliant deformable structures are integrated to initiate modifications to the aerodynamic shape, without necessitating discrete surfaces such as flapped surfaces used in more traditional configurations.

Smith et al. [9] explores the effect of cant and twist concepts on a polymorphing wing, with these two degrees of freedom added too two outboard cross-sections. The investigation shows that optimum geometric configurations for low and high-speed operating conditions can be found, where the root bending moment is constrained. The analysis presented optimised the aerodynamic configuration for flight efficiency and specific air range, whilst satisfying a bending moment constraint. Variations in the flight mechanics observed in this concept are likely to have an effect on the stability characteristics, in addition to the development of a suitable flight control system. Ajaj et al. [3, 2, 1] introduces span morphing sections to increase the aerodynamic efficiency, through reducing the induced drag by increasing the aspect ratio. Again, the root bending moment is used to constrain the design space, as this generally leads to increases in wing weight and so a reduction in the benefit of increasing the span.

Other investigators such as those at Texas A&M [7, 8, 10], have focused resources on the development of modelling and simulation capabilities to analyse morphing concepts from aerodynamic to flight mechanic models for simulation and control. Niksch et al. [7, 8] developed an aerodynamic model suitable for flight dynamic analysis. The model uses a source-doublet panel method, allowing the main lifting surface to vary chord, sweep, thickness and dihedral. Valasek [10] presents a novel adaptive controller that learns the dynamics of the modified shape, and given a set of goals generate commands to satisfy.

This paper couples analysis methods to a morphing assessment framework developed for the EU FP7 project CHANGE, to select a suitable morphing strategy and schedule morphing parameter changes to optimise the UAV geometry through the various flight phases.

ANALYSIS SOFTWARE FRAMEWORK

Prior to any meaningful investigation, an analysis framework is required, which integrates solvers for the design sub-spaces, along with an Input/ Output format from which design data can be generated. Data generated can then be used to feedback information and assist the designer or an algorithm may be used to optimise the design parameters. In this section, the structure of the low fidelity environment for design and assessment of morphing wing configurations is presented. Figure 1 presents a proposed hierarchy of the analysis/ optimisation framework. The interfaces provided offer a logical discretisation of the framework functionality, enabling pseudo-independent development of the modules.

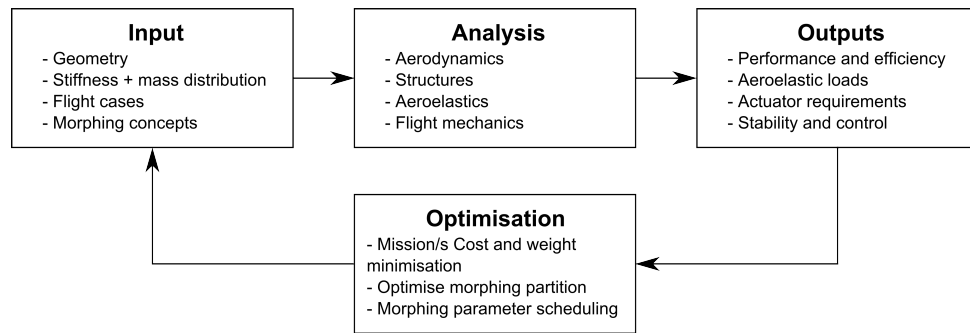


Figure 1: Software framework

Definition of the internal structure of the analysis module is ambiguous, and is largely dependent on the desired coupling between the sub-spaces. The input to this module sets; the parametric model to be used to represent the geometry, morphing concept models for geometry, inertial and structural properties and the flight cases considered within the mission. At this stage in the design process, the aerodynamic solver used is based on boundary flow method/ potential flow theory for thin aerodynamic planes (vortex lattice).

Parameterised Aero-structural Model

For conceptual investigations and assessments, reduced order parameterised models are generally used. These are typically the dominant or most influential parameters that have a significant effect on the performance of the design. This generally enables rapid execution of analysis modules to generate the data necessary to optimise the design. This enables for a wider variety of design configurations to be considered, which is critical at the conceptual design phase, to ensure sufficient coverage of the design space.

In this investigation, the geometry considered are lifting and non-lifting bodies arranged in a traditional tail-aft configuration. Additional parameters to account for modifications introduced through morphing are also included. The example presented includes morphing of a representative Micro Air Vehicle (MAV) designed for a loiter mission using span morphing to optimise for performance for low and high speed operations. Figure 2 presents the parametrisation, where $\eta_{span} = 1 - b_{ms}/b_{ps}$, the parameter used to represent the span morph.

Linear twist is also included, which modifies the twist angle at the tip by a specified angle, η_{twist} in degrees, where positive indicates wash in twist and negative washout twist.

Flight Mechanics

Using the data obtained from the aerodynamic analysis, a flight mechanics model can be developed. This can be used to investigate flight performance, efficiency and dynamics to assess the designs capacity to fulfil the mission objectives. Information required includes the so called aerodynamic derivatives and inertial properties. These are typically functions of the aircraft state immersed in a fluid environment, with flow parameters such

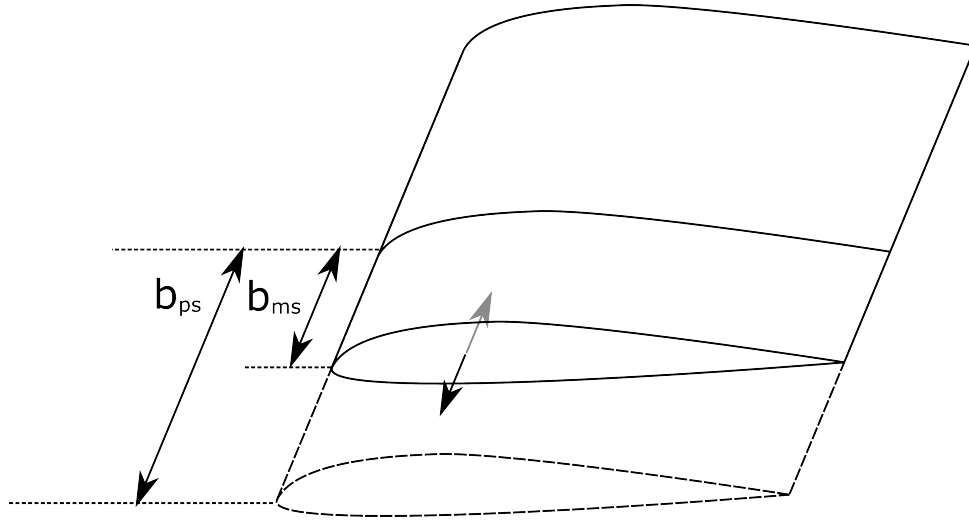


Figure 2: Parameterised span morphing of outboard wing section

as wind velocity, Mach number, Reynolds number and angle of incidence used to determine the state and compute the resultant forces generated in this flight condition. From this, performance information within the operational flight envelope can be computed. The following investigation is concerned with the mission range and endurance for loiter and dash flight phases. The following equations, taken from Hepperle [6] presents equations that show both range and endurance are directly proportional to lift to drag ratio, for electrically driven UAVs.

$$Range = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{batt}}{m}$$

$$Endurance = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{batt}}{m} \cdot \frac{1}{V_t}$$

where E^* is the specific energy stored, η_{total} is the total efficiency, m_{batt} is the mass of the battery, m is the total mass, L is the lift and D is the drag.

EXAMPLE: DESIGN OPTIMISATION STUDIES

Figure 3 presents the representative mission profile that will be used for the proceeding investigations. The UAV to be used is based on a ~ 25 kg platform, tail-aft configuration with cruciform empennage and a straight untapered, unswept wing of moderate aspect ratio. Results presented show the variation in trim properties and aerodynamic performance for variable velocity and morphing parameter. The investigation focuses on the span and linear twist distribution along the wing. Sensitivity to variation in mass and CoG position is also presented.

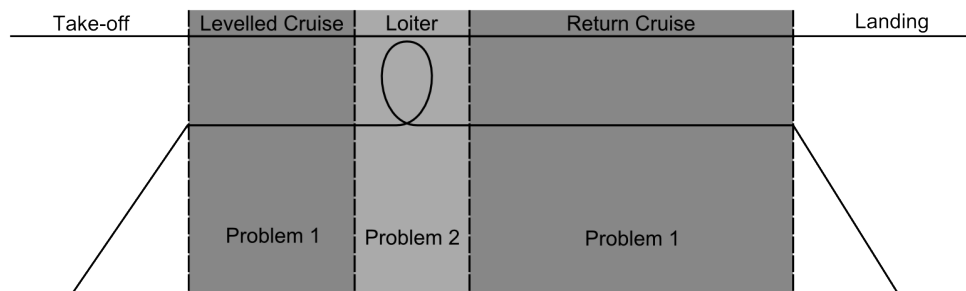


Figure 3: Mission profile

The first problem is to maximise the flight speed during the dash flight segment. The second problem

Parameter	Value
AR	6.67
$l_{Stab.}/\bar{c}$	2.43
$l_{Fin}/\bar{c}$	2.43
$S_{Stab.}/S_{ref}$	0.0848
S_{Fin}/S_{ref}	0.0607

Table 1: Geometric parameters of the reference UAV

Parameter	Value
Mass (kg)	25
CoG X Pos (% MAC)	0.3032
CoG Z Pos (% MAC)	0.2920
Ref. Pos	[0 0 0]
I_{xx} (kg.m ³)	7.5942
I_{yy} (kg.m ³)	6.5749
I_{zz} (kg.m ³)	12.7329
I_{xz} (kg.m ³)	-0.0217

Table 2: Mass properties of the reference UAV

considered is to maximise the endurance of the UAV for the loiter flight segment, where the morphing wing geometric parameters are varied to achieve this.

TEST CASE: MAV LOITER MISSION

The example geometry selected for the following investigation is based on a MAV developed for loitering mission types. The reference aircraft for the configuration is the Tekever AR4 (illustrated in Figure 4), where the mass is estimated at ~ 25 kg. Figure 4(a) presents an illustration of the platform used in this investigation, where Figure 4(b) shows the limits of the morphed geometry relative to the baseline geometry. A morphing concept applied that enables spanwise contraction is implemented through a telescopic actuation arrangement, allowing up to 50% span reduction on an outboard partition accounting for 50% of the span (25% reduction of the total span).

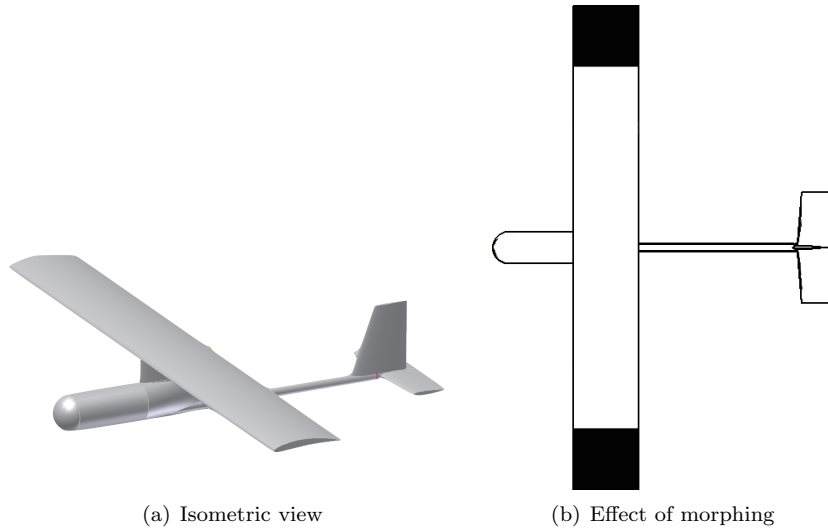


Figure 4: Representative model of the Tekever AR4

Table 1 presents some of the relevant nominal geometric characteristics, and Table 2 the mass properties.

RESULTS

The results included in this section are for the case of loiter, climb and decent flight phases. These include variations in speed and span morphing parameter. The plots presented are over a range of relative wind velocities, and morphing parameters, η_{span} and η_{twist} (where $\eta_{span} = 1 - b_{ms}/(b_{mp})$ and η_{twist} is the absolute angle at the wing tip in degrees, varying linearly between root and tip). The Angle of Attack (AoA) is presented as an absolute value in degrees, as is the stabiliser angle. The aerodynamic efficiency is normalised to the maximum aerodynamic efficiency of the nominal CoG properties.

Trim results are obtained through formulating an optimisation problem for minimising a cost function presented in Equation (1). The free parameters are α , δ_{HSTAB} and $\delta_{throttle}$, fixed states are V_t and alt , q is constrained to zero, θ is constrained to α .

$$\min(c) \quad (1)$$

$$c(\alpha, \delta_{HSTAB}, \delta_{throttle}) = (\dot{V}_t - \dot{V}_t|_{des})^2 + (\dot{alt} - \dot{alt}|_{des})^2 + (\dot{q} - \dot{q}|_{des})^2$$

where,

$$\theta = \alpha, V_t = const, alt = const, q = 0$$

Span Retraction: Nominal Results

Figure 5 presents the relevant trim information for the range of parameter variations used. These results are presented at the nominal CoG position presented in table 2 relative to the aircraft geometry presented in Figure 4 (whilst varying span morphing parameter η_{span}).

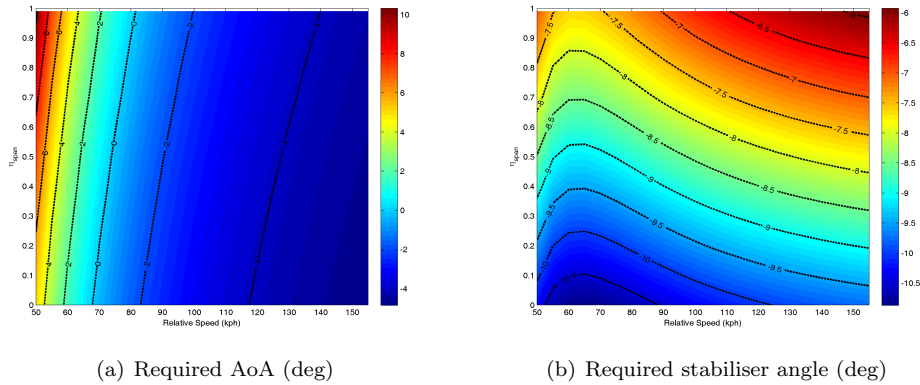


Figure 5: Trim parameters for variable span using nominal mass properties

The trim AoA presented in Figure 5(a) shows the variation with relative total wind velocity and span morphing parameter. These results infer that the required AoA to trim is generally more sensitive to variations in velocity at low relative wind speeds, where the required AoA for variation of morphing span parameter at constant velocity is nearly constant. The trend in required stabiliser angle shows a general decreased nose pitch up moment generated by the tail as wind velocity increases which is nonlinear with speed. As span is retracted, the required nose up pitching moment generated by the horizontal stabiliser decreases. Additionally, as the velocity is increased, the trim AoA decreases below 0 degrees relative to the wing plane. This implies that the zero lift AoA is negative, which is due to the camber of the aerofoil used in this example on the main wing.

Figure 6(a) presents the variation in or lift-to-drag ratio, where an optimum between 65-70 kph at maximum span. As the span is retracted, the maximum aerodynamic efficiency is observed to decrease. The velocity of the optimum aerodynamic efficiency increases as span is retracted. At low flight speeds, there is no benefit to span morphing based on the aerodynamic efficiency. The results indicate that between 105 and 110 kph, the increase in induced drag relative to the decrease in profile drag component whilst retracting span is in equilibrium. Beyond this speed, the profile drag modelled is more dominant, and so with span retraction, a marginal increase in aerodynamic efficiency is observed. The aerodynamic efficiency shown in Figure 6 also implies that the maximum range and endurance speed increases with span retraction.

Also presented in Figure 6(b) are the same results but plotted relative to the maximum value at the maximum span. The dotted contours are related to the respective parameters indicated by the colour map, where the

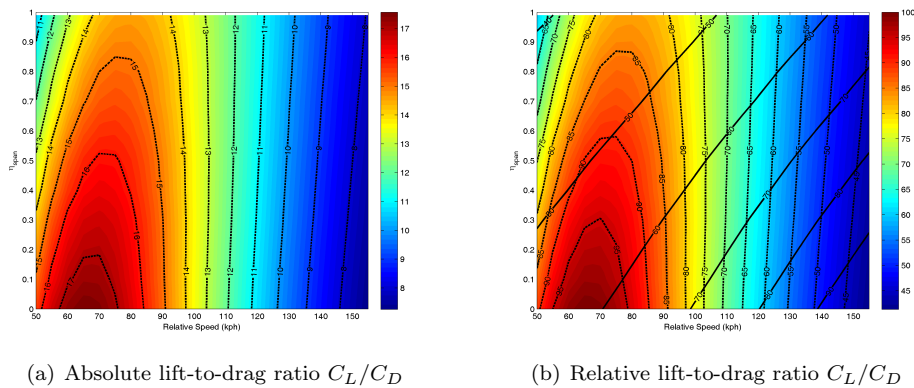


Figure 6: Aerodynamic efficiency using span retraction at the nominal mass properties

solid contours plot the root bending moments, which are normalised to the maximum root bending moment at the maximum span. These plots show that as velocity is increased, the root bending moment increases. As span is retracted, these results indicate that the bending moment also decreases. Figure 6(b) implies that as speed is increased, bending moments can be decreased with no significant loss to the aerodynamic efficiency.

The span morphing results showed that the variation of aerodynamic efficiency with speed generally increased rapidly to the optimum, and then decreased slowly beyond this point. As span is retracted, the optimum speed for aerodynamic efficiency increases marginally, also decreasing the maximum lift-to-drag ratio by approximately 8% over the full span condition. Although a decrease in the aerodynamic efficiency is observed, there is also a decrease in root bending moment of up to 15%. It is observed that as the trim speed is increased, the trend with span retraction changes. At lower speeds up to approximately 108 kph, it is the lift induced drag component that dominates the drag equation. As the trim speed is increased up to and beyond 108 kph, the parasitic drag component dominates. The model used to represent this component is an inverse function of Reynolds number, and so its value decreases with speed. In this region, retracting the span increases the lift-to-drag ratio, as the lift induced component is no longer the dominant term.

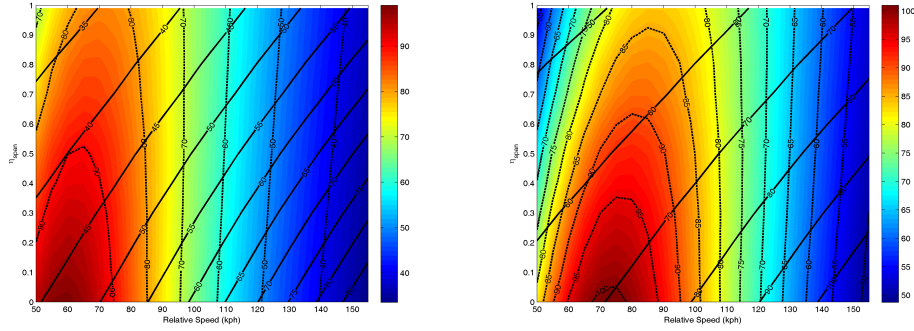
Mass Sensitivity:

To investigate the sensitivity to errors in mass estimation, or increase in mass due to implementation of a structural morphing concept, the mass is varied from -20% to +20% of the nominal mass. Mass is assumed to increase at the CoG with no change in other inertial properties. No significant change in the functional relationship between trim parameters (AoA and stabiliser angle) and mass were observed. As required lift coefficient increases, an increase in required AoA resulted.

Figure 7 shows the effect of this on the aerodynamic efficiency. Generally, these results suggest that as mass is increased root bending moments increase, as does the optimum speed for maximising each of the parameters. The optimum aerodynamic efficiency is observed to increase marginally with increase in mass. Based on the lift induced drag alone, the maximum is observed to remain constant, but the modelling of C_{D0} , this drag component decreases with increasing velocity ($C_{D0} \propto 1/Re$), thus, as the optimum speed increases so does the lift-to-drag. It must be remembered that although this parameter may increase marginally with mass, range and endurance are also functions of mass, thus it does not necessarily follow that the dimensional range and endurance increase.

The root bending moment increase is approximately proportional to the mass for a given dynamic pressure (and Mach number) related through the required vehicular lift coefficient. It must be recognised that the observed increases in aerodynamic efficiency with mass cannot be used in isolation to conclude that range and endurance increases. Although the maximum lift-to-drag increases marginally, it is greater better for a range of speeds above the optimum, the parameter values for a decrease in mass are larger at lower speeds.

The sensitivity of aerodynamic efficiency to mass and span morphing parameter showed a marginal increase in lift-to-drag ratio with increase in mass and increase in the optimum speed this is achieved. Without the zero lift drag model, these are equal. The reason for the increase in aerodynamic efficiency is that the zero lift drag coefficient component decreases with increasing speed. As the optimum speed for maximum efficiency increases with mass, the efficiency also increases due to the relative decrease in C_{D0} . This does not necessarily imply an increase in range and endurance, as the increase in mass results in an increase in required power to



(a) Lift-to-drag ratio C_L/C_D with mass -20% (b) Lift-to-drag ratio C_L/C_D with mass +20%

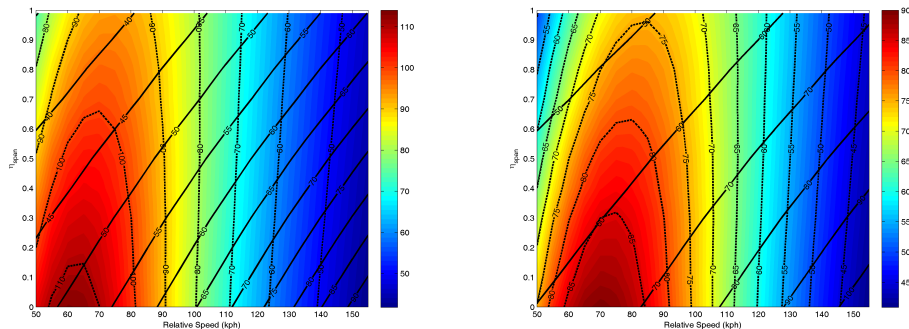
Figure 7: Aerodynamic efficiency using span retraction with variable mass

trim, and so a decrease in dimensional range and endurance. Additionally, a material decrease in root bending moment is observed, proportional to the decrease in mass.

CoG Sensitivity:

The CoG is migrated along the X-axis. Results for trim AoA whilst increasing static stability through migrating the CoG towards the nose were observed to increase. Although effectiveness of the tail is increased, due to the greater nose down pitching moment generated by the wing, a more negative stabiliser angle is required to trim. This results in a decrease in the vehicular lift, and so as was stated earlier, the angle of incidence on the wing is required to increase in order to compensate. Decreasing the static stability leads to the opposite trend, where a decrease in required angle to trim, and a positive increment to the stabiliser angle.

The results in Figure 8 show the effect of migrating the CoG in the X-axis on the aerodynamic efficiency, range and endurance parameters. In general, decreasing static stability increases the optimum aerodynamic efficiency, range and endurance parameters, whilst also decreasing the speed at which it occurs. Also the aerodynamic efficiency is increased over the range of speeds considered. Another benefit to reducing the static stability is the measurable reduction in root bending moment. This occurs as the required lift generated on the wing decreases, due to the positive increment in the tail lift.



(a) Lift-to-drag ratio C_L/C_D with CoG -25% MAC (b) Lift-to-drag ratio C_L/C_D with CoG +25% MAC

Figure 8: Aerodynamic efficiency using span retraction with variable CoG position

Linear Twist: Nominal Results

Application of linear twist is another option for morphing, where spanwise lift distribution can be modified to improve the aerodynamic efficiency. The premise is that by allowing the wing to twist, the lift distribution can be modified closer to the ideal 'elliptical' lift distribution, increasing the Oswald efficiency factor, thereby reducing lift dependent drag. Additionally, the twist can be used to alter the lift distribution to reduce the bending moments. Figure 9 presents the trim AoA and stabiliser required to fly straight and level.

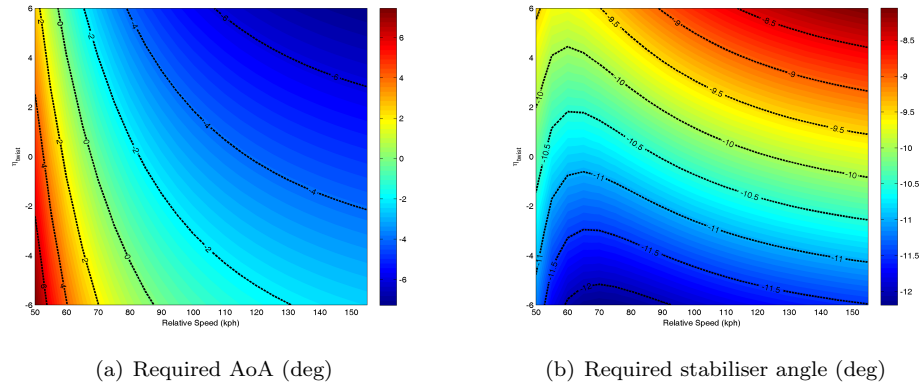


Figure 9: Trim parameters for variable twist using nominal mass properties

Figure 10 presents the aerodynamic efficiency, which is observed to increase with addition of washout twist (negative twist at the tip). From the relative plots, the bending moments are observed to decrease as the washout is increased. The optimum linear twist at maximum span is between 2 and 4 degrees washout. Introducing this twist increases the aerodynamic efficiency from 1-2% relative to the zero twist case. This is attributed to better lift distribution increasing the Oswald efficiency factor for the lift induced drag equation ($C_D \propto 1/e$ where C_D is drag coefficient and e is the Oswald efficiency factor).

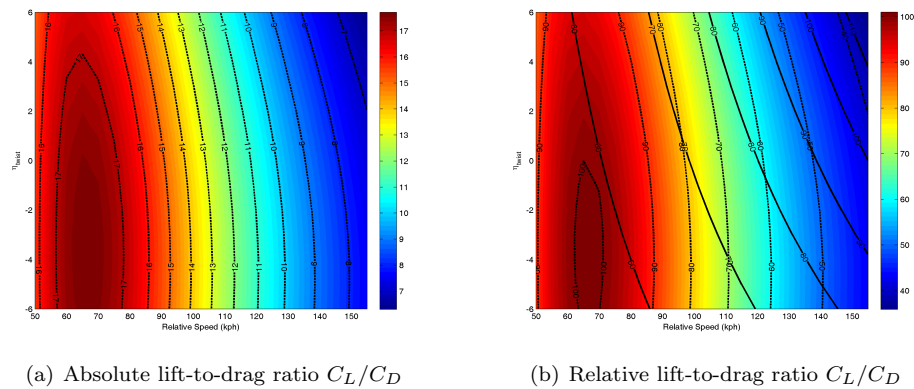


Figure 10: Aerodynamic efficiency using variable twist at the nominal mass properties

Introduction of washout twist is shown that at the optimal aerodynamic efficiency, the root bending moments are reduced by up to 5%. Furthermore, throughout the envelope, this twist is observed to provide equal bending moment relief for little change in the aerodynamic efficiency.

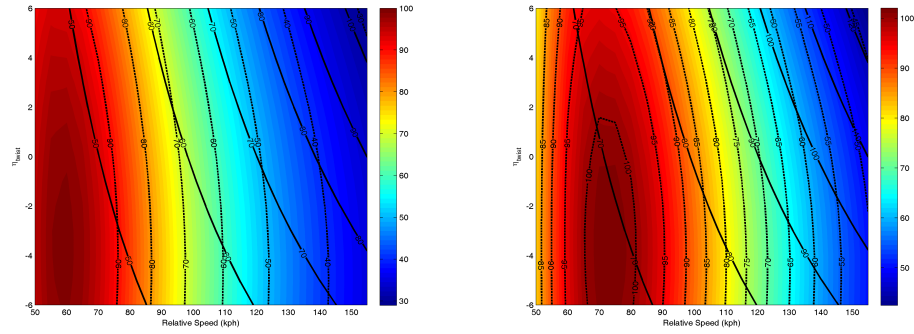
Mass Sensitivity:

Figure 11 presents the sensitivity of these parameters to mass. Generally, the bending moments are observed to decrease with decreasing mass, which is approximately proportional to the change in mass. The optimum twist appears to be unaffected by the mass, where the maximum parameter values increase marginally with increasing mass, at an increased velocity, consistent with the results in Figure 7.

CoG Sensitivity:

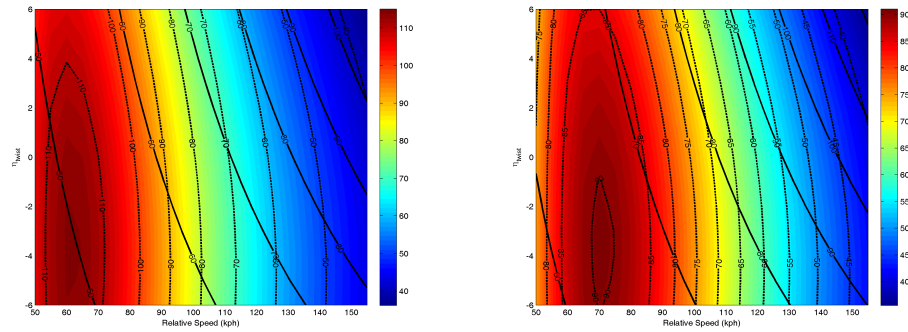
Figure 12 presents the sensitivity of aerodynamic efficiency to migration of the longitudinal CoG position. Following the results from Figure 8, the maximum parameter values increase with decrease in static stability, also reducing the optimum speed to operate at. Again the optimum twist is observed to remain relatively constant. The optimum washout twist also appears relatively insensitive to migration of the longitudinal CoG position.

Span Retraction Sensitivity:



(a) Lift-to-drag ratio C_L/C_D with mass -20% (b) Lift-to-drag ratio C_L/C_D with mass +20%

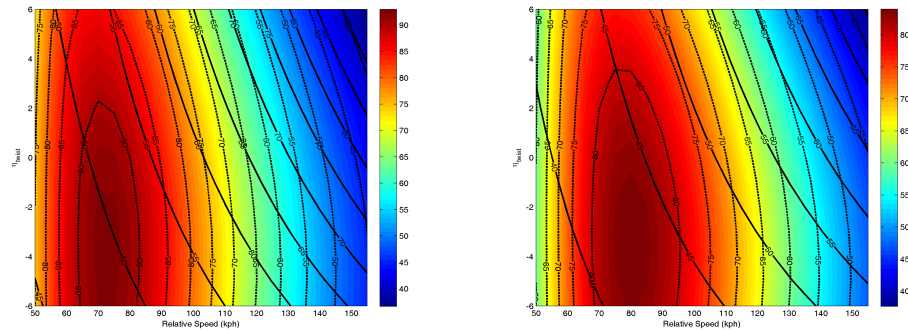
Figure 11: Aerodynamic efficiency using variable twist with variable mass



(a) Lift-to-drag ratio C_L/C_D with CoG -25% MAC (b) Lift-to-drag ratio C_L/C_D with CoG +25% MAC

Figure 12: Aerodynamic efficiency using variable twist with variable CoG position

Figure 13 shows the sensitivity of twist to variable span, with the span morphing span η_{span} set to 0.5 and 1. The optimum twist does not appear to vary considerably with decreasing span. As the span decreases, the bending moments were observed to decrease considerably, where the decrease in maximum lift to drag is observed to marginally decrease. The optimum speed increases with span retraction.



(a) Lift-to-drag ratio C_L/C_D with $\eta_{span} = 0.5$ (b) Lift-to-drag ratio C_L/C_D with $\eta_{span} = 1$

Figure 13: Aerodynamic efficiency using variable twist with variable span retraction

DISCUSSION

The trim results generated for this paper (Figures 5 and 9) showed reasonable required AoA. Results for increases in mass, migration of the CoG or span retraction whilst twisting followed expected trends and so were not included. These showed that where mass was increased, or span retracted, to maintain equilibrium in the lift-weight equation, the required lift coefficient must be increased to accommodate the increase in mass or the decrease in wing wetted area. The required stabiliser angles computed are in the order of 10 ± 2 degrees, which is alarmingly high. This indicates that the horizontal stabiliser should be redesigned to reduce these excessive deflections. Also, the estimated CoG longitudinal position is at a point where the static margin is small and close to instability.

The effect of span morphing on aerodynamic efficiency was then presented. This showed that for a non-morphing wing, aerodynamic efficiency increases to a maximum at approximately 68 kph, indicating this is both the position of maximum range and endurance for an electrically powered UAV. As speed continues to increase, the aerodynamic efficiency decays. Throughout this range, the root bending moment is observed to increase. By retracting the span, the optimum speed for aerodynamic efficiency increases, where there is a significant decrease in the maximum aerodynamic efficiency of up to 18% with span fully retracted. As speed is increased beyond the maximum, the sensitivity to span retraction diminishes, where no change in aerodynamic efficiency is observed with span retraction for a speed of 105 kph. This was attributed to an increase in the profile drag component. As the speed increases where profile drag is dominant, the optimum aerodynamic efficiency is obtained where the span is fully retracted. These results would suggest that there is little aerodynamic benefit to span retraction. However, it is observed that by retracting the span, significant reduction to the bending moments can be achieved, up to 15%. If the wing is designed to withstand a particular structural loading, these results imply that the span must be reduced in order to withstand the structural loading when operating at higher speeds.

The effect of mass showed that as mass was increased, a marginal increase is observed in the maximum aerodynamic efficiency, with a marginal decrease when decreasing mass. This is attributed to the relationship between the zero lift drag and air speed and the change in optimum speed for maximum lift-to-drag ratio. More importantly is that the root bending moments decrease is proportional to the decrease in mass. This result indicates the importance of relative wing mass prediction for a non-morphing wing to a morphing one. Assuming that a non-morphing wing is designed to accommodate the speed variation (from 50-155 kph), questions that can be posed include: what is the allowable change in mass, and what is the allowable decrease in structural stiffness to resist bending moments introduced by integrating morphing, in which the morphing wing is the better choice to an equivalent non-morphing wing. This parameter cannot be used in isolation, because the range and endurance also depend on the mass, and so the reduction in these must also be taken into account.

The sensitivity to longitudinal CoG was then presented. These show that decreasing static stability both increases aerodynamic efficiency and decreases bending moments. This is due to the decrease in wing lift coefficient. It was shown in Figure 5(b) that the trim stabilizer angles are large. Assuming that the static stability is required to increase, this would suggest that an increase in the optimum trim speed, along with increased root bending moments. As such this indicates the importance of a well designed horizontal stabiliser for performance, range and endurance estimates. The systems level analysis is essential in determining the maximum aerodynamic efficiency and the optimum speed for this.

Results were then shown for implementation of linear wing twist. In general, the results suggested that a washout twist of between 3-4 degrees was required to obtain the optimum lift-to-drag ratio. As speed increased from the optimum, marginal gains in efficiency can be obtained by reducing the wash out angle by up to a degree. Figure 13 shows clearly that as span is reduced, that marginal gains in the aerodynamic efficiency are observed above 105 kph. Bending moments can also be modified using twist morphing, generally decreasing bending moment with increasing washout angle through shifting the loading inboard. Structurally, this could be beneficial to reduce bending moments, without significant loss in the aerodynamic efficiency. The effect of mass, longitudinal CoG and span morphing have little effect on the washout angle required for maximum aerodynamic efficiency. As such the introduction of a single linear twist to optimise the aerodynamic efficiency could far outweigh the introduction of a morphing mechanism to vary this parameter with little aerodynamic benefit. However, due to the relative insensitivity of aerodynamic efficiency to this morphing parameter, bending moments can be decreased at little aerodynamic cost. To ascertain the optimum strategy it is necessary to compare the aerodynamic efficiency relative to increases in weight (due to themorphing mechanism).

From all the results, it is clear that for this example, the loiter mission speed is between 65 and 70 kph. Span morphing is relevant if the bending moments that a non-morphing wing can withstand does not meet

the threshold required to fly at the dash speed. Alternatively, if by introducing morphing, the reduction in bending moments experienced leads to a decrease in wing weight, or the wing weight increase is offset by aerodynamic benefits from reduction in skin friction drag, which lead to an increase in range, endurance or overall mission performance. Linear twist can be introduced to optimise the lift distribution, such that the wing operates close to an elliptic distribution, leading to an increase in aerodynamic efficiency. For this, the change in aerodynamic efficiency to modification of the linear twist is negligible. This would suggest that a linear twist morphing concept is unlikely to be of use for purely aerodynamic reasons. Additionally, introducing twist generally increases the demand on the horizontal stabiliser, through increased required angles of incidence. However it was also shown that by introducing twist, bending moments can be reduced, without significant decrease to the aerodynamic efficiency.

CONCLUSIONS

This paper presented results for a range of flight speeds, to simulate the variation in aerodynamic efficiency, range and endurance for a morphing UAV with electrically driven, power based propulsive system. The morphing parameters selected in the investigation were span and twist. Span results showed that aerodynamic benefits for modifying the span are minimal, yielding marginal increases in lift-to-drag at higher speeds. However, the bending moments are observed to be significantly reduced. It is postulated that span morphing can either be used because a practical non-morphing structure cannot support the bending moments, or that a morphing equivalent can be designed that increases in mission performance outweighing any possible increase in weight introduced by the concept.

Linear twist was shown to increase the aerodynamic efficiency. Negligible changes in optimum twist were observed, with aerodynamic efficiency relatively insensitive to variations in linear twist. Although little aerodynamic benefit can be gained from allowing linear twist to vary beyond the optimum value, reduction in bending moments are observed for little loss in aerodynamic efficiency by increasing the washout twist.

Sensitivity of each of the results were shown to mass and longitudinal CoG position. Generally, varying these parameters has little effect on the effect of span or twist morphing. Increasing mass leads to a significant increase in the maximum aerodynamic efficiency, optimum speed, and bending moments. This does not however lead to increase the dimensional range or endurance, as these parameters are also functions of mass. The effect of moving the aircraft CoG toward the nose increases static stability, decreases aerodynamic efficiency, increases optimum speed and root bending moments.

Finally, the effect of varying span and twist was investigated: the results imply that this does not effect the trend with twist. As span is retracted, the maximum aerodynamic efficiency diminishes consistent with the span retraction results, also showing at speeds above 105 kph, retracting span increases efficiency.

Further work is needed to widen the mission, such that the optimum morphing limits and technologies can be selected to maximise performance, range and endurance. The effect of including bending moments on the mass of wing, and the effect of change in mass due to implementation of morphing concept/s must be accounted for, to optimise the mission performance. Development of figures of merit that relate the sensitivity of the design to morphing parameters and errors in the mass properties estimation are required to provide comprehensible information to designers implementing morphing concepts.

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