MULTIDISCIPLINARY DESIGN OPTIMIZATION OF AN ACTIVE NONPLANAR POLYMORPHING WING

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Abstract

Multidisciplinary Design Optimization (MDO) has been performed on the retrofitting of a morphing wing system to an existing conventionally designed commercial passenger jet. Refined studies have been undertaken in order to confirm initial findings using high end, low fidelity aero-structural analysis together with a full engine model and integrated operational performance algorithm. Performance in off-design conditions has also been investigated in order to determine whether such benefits that have been previously demonstrated with fixed winglets could be maintained throughout the entire flight envelope with morphing technology. Preliminary results indicate a specific air range performance increase of approximately 4-5% over that of fixed winglets through all flight phases within the aircraft range of operation including off-design conditions.

1 Introduction

Development in the field of Multidisciplinary Design Optimization (MDO) has been notably intense in recent times due to the increase in complexity and performance demands placed upon engineering systems. Within commercial aviation, economic necessities of driving down operating costs in addition to environmental pressure to improve aircraft efficiency have resulted in MDO becoming an attractive field of research as a means of maximizing aircraft low-speed and high-speed performance while minimizing the cost of operation.

One of the key areas of research into improving the efficiency of modern transport aircraft has been in the analysis and development of non-planar wing tip devices that are intended to reduce the auto-vortex-induced drag of an aircraft wing. The vortex-induced drag typically comprises 30-40% of the total drag in cruise, and up to 90% of the total drag in second segment climb due to the high lift coefficients [1]. Efficiency in this area is thus critical to all facets of aircraft performance. The concept of wing endplates for improving wing efficiency first appeared as early as the 19th century [2], with studies by Hemke [3] and Mangler [4] both indicating that the induced drag reduction outweighed the increase in viscous drag due to the endplate wetted area. End plate concepts were largely dismissed due to off-design performance, interference and airflow separation issues at the wing-plate junction, and it was not until Whitcomb developed fixed non-planar wingtip devices at NASA Langley [5], that a non-planar concept gained increasing acceptance within the industry. Whitcomb claimed that the end plates required as much detail as the main wing itself, hence the name ‘winglet’, with a need for significant side force generation to manipulate the inflow and outflow. Initial experimental testing revealed the potential for up to 20% induced drag reduction resulting in a 9% cruise lift to drag ratio improvement, more than double that of an in-plane span extension of equivalent root bending moment. Gilkey [6] followed this up with wind tunnel testing of the design on a

McDonnell Douglas DC-10, with results indicating double the cruise drag reduction of a tip extension. Whitcomb's work proved to be the catalyst, as soon incorporation of his winglets began on many new transports, including the Gulfstream III and IV business jets, the Boeing 747-400 and McDonnell Douglas MD-11 airliners, and the McDonnell Douglas C-17 [7]. Kroo [8] employed a more advanced wing weight model and viscous drag incorporation into his studies, coupled with Trefftz plane theory, which revealed the 'Prandtl' or box wing to be the most efficient morphology for a given height, span and lift, closely followed by 'C wings' and winglets, with the potential for up to 30% induced drag reduction for a height-to-span ratio of 0.2. This is in agreement with earlier research from von Karman & Burgers [9] back in 1935 as well as DeYoung [10]. Aviation Partners, Inc. [11] have developed both blended and spiroid winglets, the former being claimed to give a 6% drag reduction for the Boeing 737 and the latter 6-10% fuel savings.

In this paper, multidisciplinary design optimization has been applied to the problem of maximizing the performance benefit through the retrofit of a morphing non-planar outer wing system to a commercial narrowbody aircraft. The work undertaken for this paper involves a two-level combined aero-structural-control-performance optimization that requires the coupling of aerodynamic and structural design modules. Winglet systems are already known to significantly enhance the instantaneous specific air range (SAR) through drag reduction, and thus, through block fuel reduction in which an approximate 4% block fuel burn saving is predicted on ranges of 2000nm upwards [12]. However such improvements only occur at the design lift coefficient that the winglet has been optimized for. Morphing technology presents the possibility of actively reconfiguring the outer wing system geometry for the given flight condition to provide maximum benefit throughout the entire aircraft operational envelope.

2 The MORPHLET Concept

The objective of this paper has been to perform preliminary sizing of an active polymorphing wing system that is to be retrofitted to an existing conventionally designed commercial jet. An active polymorphing system is one that allows combined scheduling of localised multi-directional geometry changes according to design intent. The proposed MORPHing wingLET, or 'MORPHLET', consists of an inner partition that alters the aileron wing panel, while retaining the fixed structural span, with up to three outer partitions replacing wing panels outboard of the aileron, as illustrated in Fig.1. Investigation has been undertaken through development of a multidisciplinary design & optimization suite, allowing for variation of local twist (θ) and cant angle (Γ) for each of the partitions, in addition to the span (b) and taper ratio (λ) of the outer partitions of the MORPHLET to establish an optimal configuration. SAR and climb gradient (γ) improvements, take-off and landing field length reductions and block fuel burn savings all occur as a consequence of the prospective reduction in vortex-induced drag generated via re-optimization of the span loading of the wing system. Further aims of the retrofit exercise have been to establish additional potential gains of the MORPHLET concept with anticipated benefits being to:

- Optimize lift to drag ratio during low-speed
- Reduce noise and engine maintenance
- Improve loadability
- Optimize different flight phases
- Improved initial cruise altitude (ICA) and maximum speed
- Improve performance during abnormal procedures
- Improve stability at different flight control system modes
- Reduce operating economics
- Expand buffet and flutter envelopes, reduce vibration, tailor stall
- Improve aero-elastic performance
- Permit span increases while maintaining conformity with ICAO regulations

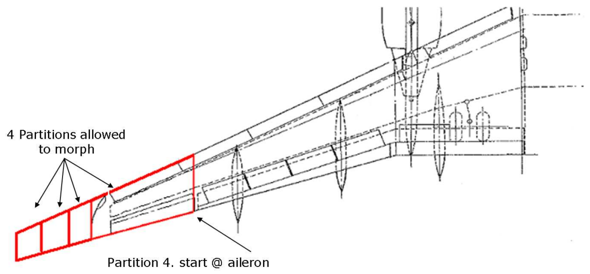

Fig. 1 Multiple partition MORPHLET retrofit concept.

The benefits of the active polymorphing system are a result of the ability for the geometric schedules, such as twist and cant angles, to be reconfigured so as to optimize performance for each flight segment. This also includes the ability for minimum cant angle (from the vertical) to reduce span to within ICAO regulations for airport compatibility. This is in contrast to current wing tip technology whereby the geometric dimensions are fixed and thus may only be optimized for a specific flight condition, i.e. a design lift coefficient, and can have negative effects on performance in other scenarios. For this reason, comparisons in the analysis for all performance improvements are made with reference to the current wing fence employed on the A320, purported to give 1-1.5% total drag improvement for on-design condition. Certain benefits of the MORPHLET concept, such as the improved noise and engine maintenance, expanded flutter envelopes and improved stall characteristics, are not yet captured by the software. Previous studies have already been undertaken on the structural validity of the concept along with preliminary aerodynamic analysis [13], with results indicating typical SAR gains of 5.8%, a combination of an induced drag reduction of 18% and an elastic wing weight (wing box & systems) increase of 15%. Results from this paper are compared with those from [13], where investigations were focused on a 4 partition approach, in order to gain further insight into the validity of increasing the number of morphing partitions.

3 The Multidisciplinary Design and Optimization Suite

The MDO suite has been created and developed as a high end, low fidelity analysis tool for conceptual aircraft design optimization. The suite has the capability of running a constrained multi-objective function optimization problem using a genetic algorithm [14] that can be coupled with a Nelder-Mead simplex [15], using a modified form of the Kreisselmeier-Steinhauser (KS) function [16] for conversion into an unconstrained composite objective function. The MDO suite features many expert aerodynamic and performance modules as well as a new structures code for wing weight estimation, named ‘UC700’, which includes Wing Equivalent In-plane Representation (WEIR) for wing systems and secondary wing weight predictions, in addition to empennage resizing for static stability & control. This provides a complete aero-structural-control-performance analysis, with the ability to consider a large number of aerodynamic, structural, control, engine and performance parameters. An outline of the MDO suite used is given in Fig.2, where ‘SS’ refers to the sizing stage.

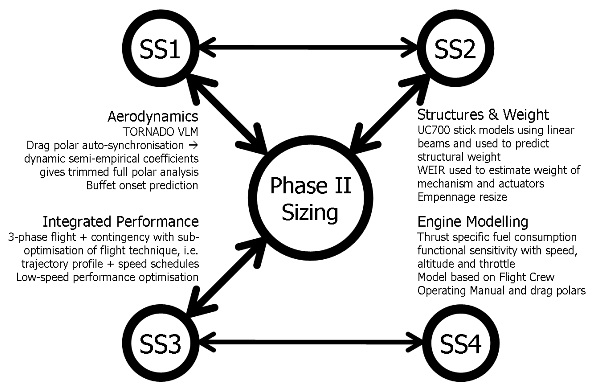

Fig. 2 MDO Suite current schematic diagram.

3.1 Aerodynamics

The MDO suite utilizes the Tornado Vortex Lattice Method (VLM) [17] for the aerodynamic predictions. Tornado is a linear aerodynamics code, thus has the limitations in application that come with this, such as the discounting of wing thickness and viscous effects, leading to a lack of conformity for angles above 8-10° for slender wings. These limitations mean that Tornado cannot be used within certain parts of the flight envelope, and other expert modules must be developed to investigate potential issues, such as buffeting and static divergence. 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, as well as both take off and landing phases. These are therefore the flight stages in which most of the research and analysis has been undertaken. More advanced nonlinear aerodynamic predicting tools would not be practical for use in this work due to the substantial increase in solution time that would result. Fig.3 gives the aircraft lattice model as displayed in Tornado. Expert aerodynamic modules incorporated into the MDO suite include auto-trimming functionality. This acts to equalise the heave & surge forces, and aerodynamic coupled with engine pitching moments through iteration of the aircraft angle of incidence, the tail setting angle and the engine throttle setting until convergence to a trimmed state of steady, level flight. The aircraft zero lift drag is computed via a skin friction, compressibility & form drag prediction module that is inferred from the drag polar of the datum aircraft. Through auto-synchronisation the coefficients are dynamically generated according to a set of semi-empirical expressions defined a priori. This coupled with the Tornado vortex lattice method gives a trimmed full polar aerodynamic analysis. A Buffet prediction module, based on [18], has been added to the aerodynamic solver to allow for an accurate prediction of buffet onset. The module allows the user to enter a buffet envelope from flight test data or to use a generic reference buffet onset. It then interpolates this data using the variations in taper, wing sweep, thickness, camber and aspect ratio (AR) to ascertain a critical lift coefficient value at which buffet onset occurs.

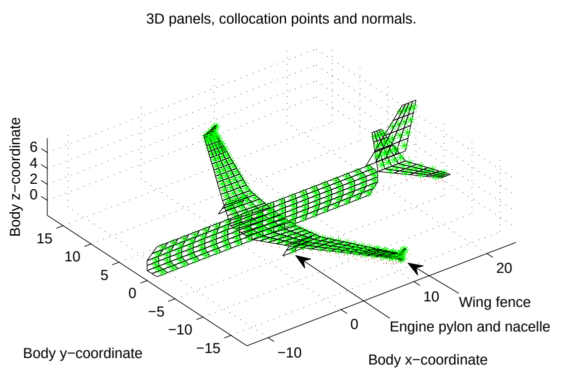

Fig. 3 A320 Tornado model with wing fence displaying panel normals & collocation points.

The baseline aircraft vortex slings that map the path of the vortices shedding from the aircraft model are displayed in Fig.4.

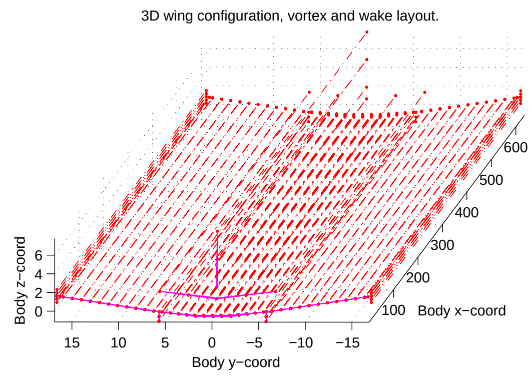

Fig. 4 A320 Tornado model displaying vortex slings.

3.2 Structures and Performance

The structural analysis module is a compromise between low fidelity models, based on purely statistical data of existing aircraft, and high fidelity non-linear finite element models. The analysis is based on linear beam theory and employs a novel multi-element sizing strategy, where the wing box is discretised into elements in correlation with the aerodynamic panels from the vortex lattice. A local load factor is then estimated for each element via preliminary load case sizing for *gust load*, *aileron roll* and *maximum manoeuvre* flight cases, in accordance with E.A.S.A. regulations, to determine the critical sizing case for each wing station. The inertial relief of the wing mass, fuel systems, engine installation and landing gear are all incorporated in addition to the aerodynamic loads for sizing. The structural model provides the flexural properties of the wing at different spanwise locations, and provides a detailed weight breakdown of the wing, including primary wing weight ($W_{wing_{pri}}$), secondary wing weight ($W_{wing_{sec}}$) and wing systems weight ($W_{wing_{sys}}$). Another novel feature of the model is a quasi-static aeroelastic check to predict the deformed shape under external loads and to assess the effect of the wing deformation on aircraft drag. The expert structures module includes the capability to optimize the rib pitch & orientation, and spar thickness & position, as a means for minimizing the wing weight and tailoring the torsional rigidity. Further functionality includes static divergence and control reversal prediction modules. Finally, the model is capable of handling complicated wing geometries, such as non-planar wings, and it caters for investigation of a wide range of materials for different wing box components.

Functionality for resizing the empennage has been implemented. The empennage is rescaled for the new test configuration as part of the optimization procedure, in order to meet requirements relating to crosswind landings, engine failure, and longitudinal & lateral stability & control performance, with new empennage weights calculated using Linnell's method [19]. The secondary wing weight prediction for new configurations is based on semi-empirical equations from Torenbeek [20] and the changes in such variables as the wing geometries and control surface characteristics & sizing criteria. It accounts for secondary weights such as the primary and secondary control surfaces, high-lift devices at the leading and trailing edges, as well as the leading and trailing edge structure.

The aero-structural-control code has been upgraded to include performance analysis into the optimization scheme. The performance analysis module is based on Isikveren's fractional change theory [21], whereby fractional deltas of the basic geometric and flight condition parameters can be incorporated into fundamental equations for performance predictions to give estimated fractional changes in such parameters as block fuel burn, maximum lift coefficients, reference landing approach & stall speeds, take off & landing field lengths and rates of climb. Such parameters allow for the expansion of the flight envelope of the optimization analysis.

3.3 Validation

There has been comprehensive validation of the suite in order to guarantee credibility of predictions of the benefits from the morphing wing system, with particular emphasis on the key aerodynamic predictions required for the MDO suite. The main areas of validation include the main wing local lift curve slope variation with Mach number, improved via integration of the Datcom correction [22] into the Tornado VLM, as well as the zero lift pitching moment coefficient variation with Mach number, of particular importance to the trimming functionality. In addition the main wing span loading has undergone analysis, where the effects of the kink and trailing edge were modelled as accurately as possible with the addition of surfaces to act as pylons within the aircraft wing model, as can be seen in Fig.3. Comparisons for each validation case has been made with flight test data.

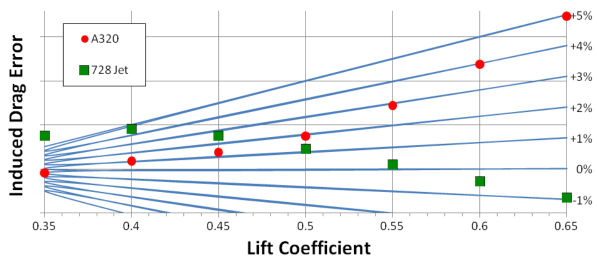

Fig. 5 Induced drag validation for the A320 and 728 Jet.

Finally the vortex induced drag, which is critical in the analysis of non-planar polymorphing wings, was analysed and validated comprehensively via comparison against values obtained using the REVDRAG expert module developed by

Isikveren [no reference available] that acts to derive the constituent drag coefficients from the aircraft polar. Results for the vortex-induced drag validation are given in Fig.5.

3.4 Multi-Objective Function Analysis

The KS function has been incorporated into the suite to allow for constrained multi-objective function optimization analysis. The KS function, the method for which is outlined in [23], acts to convert such a problem into an unconstrained composite objective function that can then be optimized by the suite. It does so by creating a pseudo-objective function that normalises and combines all bounded, inequality & equality constraints and objective functions, by use of an exponential function, into a single unconstrained composite objective function. The individual objective functions can be weighted in terms of their overall importance by utilization of a geometric fitting function 'β' value that has been incorporated into the method, as suggested by [24]. In addition the Nelder-Mead simplex has been incorporated into the MDO suite to combine with the genetic algorithm as an optimization suite cocktail, which acts as a very effective local optimizer once an initial solution has been ascertained from the genetic algorithm.

4 Problem Formulation and Procedure

For the analysis an optimization procedure was undertaken assuming a 2 partition (aileron plus new outer panel) configuration that is to be retrofitted to the Airbus A320-200 aircraft, with a number of different flight conditions being considered. The objective function selected for optimization was the aircraft SAR, and all comparisons were made with reference to the current baseline A320-200 aircraft complete with incorporation of wing fences, which have been determined to give a SAR increase of 1-1.5% over the planar wing. The partitions are initially optimized geometrically in terms of local span and taper ratio for the Maximum Passenger, Maximum Range (MPMR) Initial Cruise (FL350, M0.78) flight condition (ICA) for the baseline aircraft. This flight stage has been selected for sizing as it is the cruise condition of maximum aircraft gross weight, thus highest trim operating lift coefficients and vortex-induced drag. The partitions are then re-optimized as ones that can morph in terms of cant angle and twist to give the optimal operating schedule for the other flight conditions subject to analysis, those being Short Range (SR) Initial Cruise, Mid Cruise (FL390, M0.78) and Final Cruise/Start Descent (FL390, M0.76), with the relevant fuel burn taken into consideration from flight test data. The main parameters of optimization were decided upon based on the findings of [13], whereby it was discovered through sensitivity analysis that the lift to drag ratio had the highest sensitivity to local cant and twist angles, thus less significant variables such as local camber, thickness and the weight penalty due to system complexity have been neglected from the current optimization procedure. A number of constraints have also been implemented, such as those preventing an increase in Take-Off and Landing Field Lengths (TOFL and LFL respectively), or a reduction in leading edge sweep (Λ_{LE}) that may cause potential drag divergence or stall problems not captured by the linearised aerodynamics code. For this same reason the taper ratio variation has also been removed from the genetic algorithm and replaced with a co-linear span extension of the main wing. Cant angle (Γ), with the datum taken as the vertical axis, is constrained to positive values and limited up to the previous partition cant angle. The local twist washout/washin (θ) across each partition has been constrained to $\pm 3°$ in accordance with wing box structural tolerances established in [13]. A constraint limiting the tip chord to a minimum (600mm) in accordance with manufacturing limitations has been implemented, which in addition to the taper ratio constraint thus serves to impose an upper limit on outer partition span. The optimization problem statement can thus be stated as follows:

$$\begin{aligned} &min \quad (-SAR) \\ &w.r.t. \quad b_{P2}, \theta_{P1}, \theta_{P2}, \Gamma_{P1}, \Gamma_{P2} \\ &s.t. \quad TOFL \leq TOFL_{A320\text{-}200} \\ &\qquad LFL \leq LFL_{A320\text{-}200} \\ &\qquad \Sigma b_{min\Gamma} \leq 36m \\ &\qquad c_{tip} \geq 600mm \\ &\qquad \Lambda_{LE} \geq \Lambda_{LE\ A320\text{-}200} \\ &\qquad -3^\circ \leq \theta_i - \theta_{i-1} \leq 3^\circ \\ &\qquad 0^\circ \leq \Gamma_i - \Gamma_{i-1} \leq 45^\circ \\ &\qquad 0^\circ \leq \Gamma_i \leq \Gamma_{i-1} \end{aligned}$$

In addition to this, a low-speed performance check has been included in the analysis. An optimization for the climb flight condition, at the FL260 switch to constant Mach number for maximum specific excess power, has been undertaken for cant angles and local twists with purely lift to drag ratio as the objective function, as a measure of climb performance. Finally a multiobjective run has been performed, incorporating all flight conditions and a number of performance parameters into a single composite objective function.

5 Results

5.1 Initial Cruise, Max Passenger, Max Range Sizing Case

The focus of the analysis has been on the Initial Cruise, Max Passenger Max Range sizing case, as this is the flight condition at which the MORPHLET system is anticipated to give the highest gains, as it is the flight condition of greatest Instantaneous Gross Weight (IGW), and thus trim lift and vortex-induced drag coefficients.

The optimized configuration demonstrates that the largest gains in SAR are achieved

Flight Condition	$\Gamma_{P1}(^\circ)$	$\Gamma_{P2}(^\circ)$	$\theta_{P1}(^\circ)$	$\theta_{P2}(^\circ)$
Initial Crz $_{MPMR}$	48.15	20.95	2.66	-2.90
Initial Crz $_{SR}$	47.24	24.05	-0.28	-2.62
Mid Crz	47.24	35.31	0.44	-2.73
Final Crz	47.26	31.65	0.50	-2.88
Climb	47.24	12.27	2.03	-2.65

Table 1 Optimal geometric schedules for each flight condition.

through significantly small cant angles (large dihedral) and thus large height-to-span ratios, see Table.1. The results for the ICA maximum range optimum configuration compared with the datum aircraft as well as those of an equivalent *planar* span extension of the optimal design are presented in Table.2. Though planar span extensions offer larger aerodynamic improvements, the benefit of this is offset by the larger increase in aircraft weight through the surge in wing bending moment. This variation in wing bending moments is displayed in Fig.6. The increased loads translate into the requirement for a significantly strengthened and thus heavier wing section for all spanwise locations, as is evident in Fig.7. The optimum configuration for this flight case was determined to offer a SAR improvement of approximately 6% over that of a fixed wing fence. The breakdown for this figure is provided in Table.3, whereby the new geometric schedule offers a 16% global vortex-induced drag reduction and an approximate 9% lift to drag ratio improvement, of the same magnitude as that predicted by Whitcomb [5].

Flight Condition	C_{Di}	L/D	W_{wing}	MTOW	SAR
Initial Crz $_{MPMR}$	-15.85	6.93	8.79	0.92	5.96
Initial Crz $_{planar}$	-22.73	8.24	33.89	4.16	3.92
Initial Crz $_{SR}$	-15.31	4.73	2.37	0.19	4.53
Mid Crz	-16.69	6.05	5.47	0.60	5.42
Final Crz	-16.17	5.96	4.24	0.44	5.50
Initial Crz $_{fixed}$	-11.14	4.74	8.79	0.92	3.79
Mid Crz $_{fixed}$	-11.58	4.61	8.79	0.92	3.66
Final Crz $_{fixed}$	-11.52	5.32	8.79	0.92	4.36

Table 2 Percentage deltas in key performance parameters.

These results agree very well with previous studies [13] in terms of vortex-induced drag improvements. However wing load alleviation incorporation in the current structural model, with previous results based entirely on wing equivalent in-plane representation (WEIR), has seen the elastic wing weight increase fall to under 10% from 15% for the optimal schedules. As a consequence the specific air range improvements predicted via the new suite are superior, compared with 4-5% seen previously.

ΔS_{ref}	=	-0.93%	$\Delta W_{wing_{pri}}$	=	12.34%
Δb_{ref}	=	2.92%	$\Delta W_{wing_{sec}}$	=	-0.68%
ΔAR	=	6.93%	ΔW_{wing}	=	8.79%
ΔC_L	=	0.95%	$\Delta MTOW$	=	0.92%
ΔC_{Di}	=	-15.85%	$\Delta L/D$	=	8.79%
ΔC_{D0}	=	1.29%	ΔSAR	=	5.96%

Table 3 Initial Cruise, Max Pax, Max Range SAR improvement breakdown.

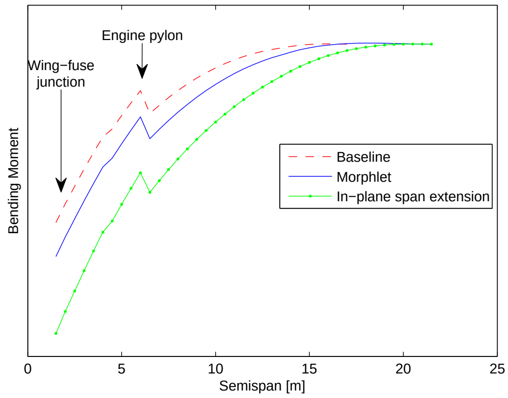

Fig. 6 Comparison of spanwise wing bending moment distribution for critical load sizing, M0.78.

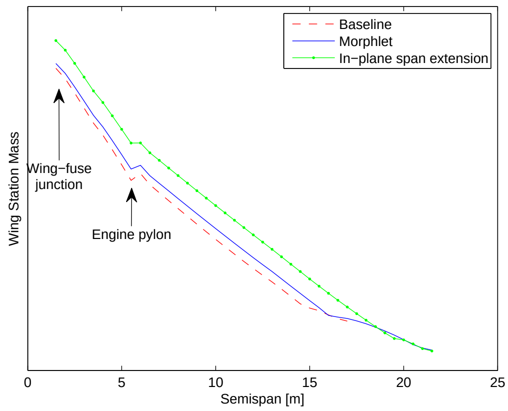

Fig. 7 Spanwise wing mass distribution comparison.

It can be observed through the design refinement thoughout the optimization procedure, see Fig.8, that the optimization process is driving the design toward mimimum permissible cant angles, and that via expanding the boundaries of the structural code to cater for negative cant angles it is perfectly viable to assume that the design would potentially lead toward that of a C-wing as predicted by Kroo [8].

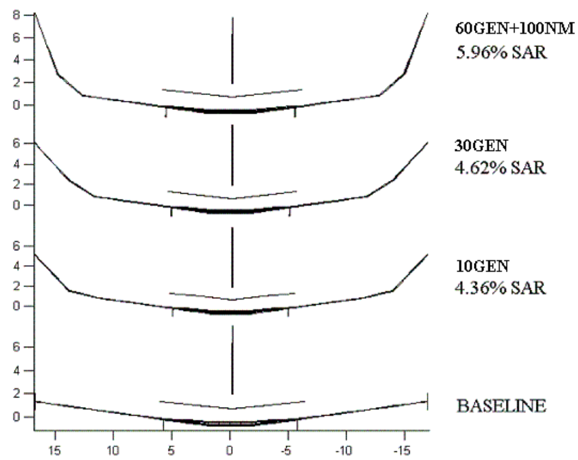

Fig. 8 Incremental improvements in design through the optimization procedure.

5.2 Off-Design Conditions

In order to quantify the performance benefits of the MORPHLET wing system in off-design conditions for varying stage lengths there have been a number of cases analysed. Optimization runs have been performed for a shorter range (SR) stage length flight case for Initial Cruise (ICA), Mid Cruise (MCA) and Final Cruise (FCA) Altitudes. Performance results for each are presented in Table.2. In addition, the relative merits are given in each of these off-design conditions assuming the retention of a *fixed* wing structure and morphing geometric schedule, that being the optimum for the Initial Cruise, Max Passenger Max Range mission case, as a means for analysis and comparison with a fixed wing system. The optimised wing planforms are also given in Fig.9, with schedules given in Table.1. Each off-design condition, despite a reduction in wing weight due to reduced wing loading, offers a reduced SAR saving compared to the MPMR improvement. When adapting the MPMR optimum geometry and wing structure, thus modelling a fixed winglet, the SAR improvements are further reduced, thus underlining the deficiencies of fixed wing systems.

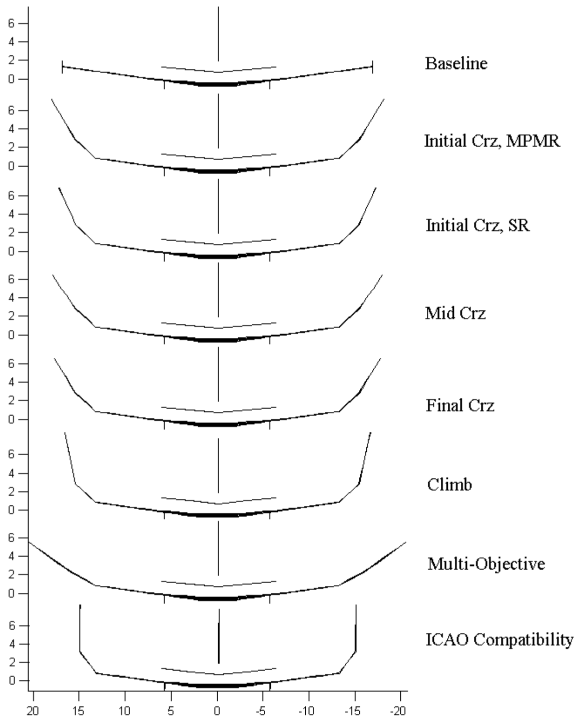

Fig. 9 Comparison in optimal wing geometries across the flight phases.

Results indicate that the morphing wing is able to introduce similar levels of performance as for the MPMR case, though as expected the SAR improvements off-design are slightly lower. Each optimum design, however, exhibits a tendency for minimal inboard cant angles, and they deviate most in the cant angle of the outer partition. Each also has a tendency for loading the inboard MORPHLET section highly with a large twist angle, and unloading at the tips with largely negative wing twists. This is visible in the span loading comparison provided in Fig.10 for the ICA maximum range case.

The low speed climb performance of the

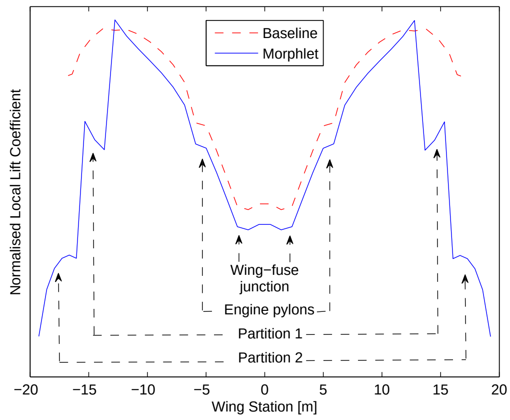

Fig. 10 Comparison in main wing span loading for optimized and baseline configurations.

MORPHLET concept has also been included in the optimization analysis. Subject to outright lift to drag ratio as a measure of rate of climb performance, the optimum morphing wing schedule was able to achieve a significant improvement of just under 5% in this area, see Table.4, and also a notable improvement over the Initial Cruise, MPMR sizing case, while interestingly the planar span extension equivalent of the optimal configuration performed worse in this regard than the baseline aircraft.

Configuration	$L/D(\%)$
Climb optimum	4.86
In-plane span extension	-1.57
Initial Crz $_{MPMR}$	3.74

Table 4 Climb lift to drag ratio improvement with re-optimized schedules.

5.3 Multi-Objective Function Analysis

As a final exercise, a multiobjective function run has been performed in order to quantify some of the potential operational performance benefits of the MORPHLET system. This has been done via accumulating the SAR improvements for each of the four flight conditions assessed and the lift to drag improvement in climb together with improvements in the take-off and landing field lengths, the landing reference speed (V_{ref}) and the maximum lift coefficients in take-off and landing ($C_{Lmax_{TO}}$ and C_{Lmax_L} respectively) predictions from the performance module into a single composite objective function value via use of the KS method. The new problem statement for the multiobjective run is thus:

$$\begin{aligned} min \quad & (\text{-}SAR_{ICA_{MPMR}}, \text{-}SAR_{ICA_{SR}}, \text{-}SAR_{MCA}, \text{-}SAR_{FCA}, \\ & \text{-}L/D_{Climb}, TOFL, LFL, V_{ref}, \text{-}C_{Lmax_{TO}}, \text{-}C_{Lmax_L}) \end{aligned}$$

Results are given in Table.5, with the geometric schedule in Fig.9. The areas of most significant improvement are the take-off and landing field lengths, with MORPHLET achieving a 9.4% and 10.8% reduction respectively, as a consequence of maximum lift coefficient enhancements. Interestingly the optimal configuration for the cumulative flight conditions is that which gives equal benefit in Initial Cruise altitudes for both maximum and shorter ranges, with a reduced SAR improvement for Mid and Final Cruise. This also corresponds with an increased wing weight as the schedule adopts a slightly more planar form.

Parameter	*Value*
Cant Angle $_{P1,P2}$	61.31° 54.70°
Twist Angle $_{P1,P2}$	2.47° -2.04°
W_{wing}	26.96%
$MTOW$	3.02%
SAR $_{Initial\ Crz,\ MPMR}$	5.12%
SAR $_{Initial\ Crz,\ SR}$	5.12%
SAR $_{Mid\ Crz}$	3.34%
SAR $_{Final\ Crz}$	3.19%
L/D $_{Climb}$	4.54%
$TOFL$	-9.43%
LFL	-10.75%
V_{ref}	-5.5%
$C_{Lmax_{TO}}$	11.5%
C_{Lmax_L}	9.8%

Table 5 Performance enhancements through multiobjective optimization.

6 Summary and Further Work

Multidisciplinary analysis has been undertaken on a datum aircraft with wing fences in order to establish the potential gains of retroactively fitting a MORPHLET wing system, comprising of two outer partitions replacing the aileron and outboard section of the wing. Through optimizing the outer partition span for the maximum range sizing case and re-optimising the partition twist and cant angles for different flight conditions it has been determined that the morphing system not only provides a substantial 6% specific air range improvement over the datum aircraft but also is able to maintain a 4.5 to 5.5% SAR enhancement for all analysed flight phases, whereas for the fixed sizing geometry improvements fall to approximately 3.5%. Results also indicate substantial improvements to the lift to drag ratios in climb, as well as take-off and landing field lengths.

The results achieved in the studies outlined in this paper demonstrate that a morphing wing system has tremendous benefit, especially when considering that there are significant nonlinear aerodynamic properties of wing tip devices not yet captured by the software that promote the necessity for specific flight condition in-flight re-optimization. Further development is required in order to analyse the extent of potential gains beyond the current MORPHLET bounds and into the analysis of C-wings and spiroid wing morphologies. An essential aspect of quantifying the benefits of the MORPHLET system is also via extensive wind tunnel testing in order to validate the optimization and to provide additional insight into the concept.

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8 Copyright Statement

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