Adaptive C-Wing Flight Controls for a Universally-Electric Aircraft

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Optimisation of overall aircraft efficiency is mandatory for aircraft designers faced with the challenge of serving a growing demand for air transport with diminishing fossil resources. Going beyond the parameter space of conventional aircraft layouts, aerodynamic efficiency may be improved by radical new wing designs such as a non-planar C-wing. In this paper, the idea is to additionally equip the top part of a C-wing with an active poly-morphing capability, enabling the wing system to adapt to different flight phases. With this adaptive Top-Wing (TW), the non-planar wing itself can then provide sufficient handling and control authority for the aircraft. Hence, one may dispense with a dedicated horizontal stabiliser, leading to a tailless aircraft layout and further enhancing vehicular efficiency. An initial design of an electrically actuated, variable direct-camber and possibly in-direct-twist TW together with preliminary weight and actuation power estimate is presented.

Nomenclature

α	Angle of attack [°]
$C_{m,CG}$	Total pitching moments about the aircraft centre-of-gravity [-]
$C_{mo,WFNP}$	Pitching moment coefficient of the wing-fuselage-nacelles-pylons [-]
$C_{m,MW}$	Pitching moment coefficient due to Main-Wing [-]
$C_{m,adp,TW}$	Pitching moment coefficient for possible adaption of the Top-Wing [-]
$C_{m,TW}$	Pitching moment coefficient due to Top-Wing [-]
$C_{m,T}$	Pitching moment coefficient due to thrust [-]
$C_{m,LG}$	Pitching moment coefficient due to landing gear [-]
$C_{m,q}$	Pitching moment coefficient due to pitch rate [-]
$C_{m\alpha,MW}$	Pitching moment gradient due to angle of attack α [-]
$C_{m,ail}$	Pichting moment coefficient due to ailerons [-]
$C_{m,flap}$	Pitching moment coefficient due to high-lift devices [-]
$C_{m,spoil}$	Pitching moment coefficient due to spoilers [-]
i	Top-Wing incidence angle [°]

Acronyms

c	Chord
CFRP	Carbon Fibre Reinforced Polymer
cg	Centre-of-Gravity
DoF	Degree-of-Freedom

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EIS	Entry-Into-Service
EMC	Elastomeric Matrix Composite
FCS	Flight Control System
MTOW	Maximum Take-Off Weight
MW	Main Wing
OF	Optic Fibre
OFDR	Optical Frequency Domain Reflectometry
PFCS	Primary Flight Control System
SAS	Stability Augmentation System
SHM	Structural Health Monitoring
STW	Self-Trimming Wing
TED	Trailing-Edge Down
TEU	Trailing-Edge Up
TW	Top-Wing
UESA	Universally Electric Systems Architecture

Introduction

Maximising efficiency has been a technological imperative for aviation from the outset, which, depending on the property of interest, may be quantified using a variety of metrics, e.g. required thrust per mass or volume, lift generated per surface area, etc. Moreover, apart from the purely technical notion of efficiency, commercial aviation is governed by stringent fuel efficiency requirements imposed by increasing kerosene costs and emerging greenhouse gas emission costs. Consequently, the design of new aircraft is strongly defined by the desire to seize any remaining potential for improvement in aerodynamics, and even retrofits such as winglets have been installed on older aircraft to achieve modest levels of percentage savings in fuel.

In the context of a future Universally-Electric Aircraft study forming the basis of the present work, for example, aerodynamic optimization under the constraint of a high and constant (over flight time) battery mass led to a non-planar C-wing layout, which moreover, is partially capable of shape-adapting itself to different flight phases (so-called active poly-morphing[1]). In this paper, such a wing concept is detailed with emphasis place on describing the mechanism behind additional adaptive Degrees-of-Freedom (DoFs). The feasibility of this wing design is supported by providing a first weight estimate, arguing that the adaptive structural system can be installed without weight penalties if design synergy effects with a wing-installed Structural Health Monitoring (SHM) system are exploited. It is postulated that usage of such advanced materials, unconventional structural morphologies and novel actuator technologies complements future aspirations of delivering electro-mobility solutions, i.e. electrical power being the only source of force transmission and simultaneously maximising the utilisation of available net volume.

Adaptive C-Wing for a Universally-Electric Aircraft Concept

The presented work covers the characteristics and capabilities of a tailless, so-called C-Wing layout designed for a future passenger aircraft with entry-into-service (EIS) year of 2035. Dubbed the Ce-Liner[2] the study was performed by Bauhaus Luftfahrt and constitutes a novel concept for zero-emissions regional transportation. In accordance with an EIS of 2035, a variety of technologies were investigated that showed promise in complying with increasingly stricter noise and emissions requirements. The aircraft is therefore equipped with a Universally Electric Systems Architecture (UESA), i.e. electric energy is used as sole form of energy for all aircraft systems, with facility given to enabling electric propulsion powered by advanced Li-ion batteries. The baseline aircraft is designed for a range of 900 nm (1667 km) with cruise at M0.75 and altitude of 33000 ft. The main dimensions are summarised as: overall length 43.0 m, overall height of 12.9 m and the span of 36.0 m including non-planar components. This design conforms to ICAO Annex 14 Code C requirements limiting the aircraft dimensions to within a 36.0 m box. The baseline aircraft has a Maximum Take-Off Weight (MTOW) of 109300 kg, which corresponds at the same time to its Maximum Landing Weight: as the aircraft is completely battery powered, no mass reduction takes place during each mission. With a reference wing area of 172.3 m^2, the aircraft features a wing loading of 636 kg/m^2. In the aircraft weight budget, the Operating Weight Empty Weight is predicted to be 59280 kg accounting for 54.2% of MTOW, and, the installed, replaceable battery weight of 30170 kg constitutes 27.6% of MTOW.

An Overview of C-Wing Aerodynamic Charateristics

The C-Wing planform is a continuous, three-element, polyhedral wing system comprising a Side-Wing and a Top-Wing (TW) mounted above of the Main-Wing (MW). It is posited that a tailless aircraft configuration can gain advantages due to the absence of a conventional horizontal tailplane lending opportunity to reduce the overall aircraft drag and weight. Figure. 1 displays a rendered image of the Ce-Liner concept and provides an illustration of the C-Wing planform partitioning convention.

Figure 1: The Ce-Liner pre-concept study (left), and pationing convention of the C-Wing planform (right).

C-Wings differ from other multi-surface configurations, e.g. canard, bi-plane and box-wing, where the second surface usually provides a part of the lift, in the sense that the natural tendancy is for the TW to produce a down force. While the former approaches decrease the global vortex-induced drag by scheduling the loads on each of the lifting surfaces, the C-Wing achieves a vortex-induced drag reduction via the following two mechanisms:

1. Change of load distribution on the MW – the structure attached to the wingtip promotes a less pronounced decrease in local lift, and thus provide a means of a reduction in MW related vortex-induced drag
2. Forward tilting of the lift vector on the TW – the MW generated downwash flowfield seen at the TW produces conditions where a “thrusting effect” can be exploited

While there is scope to improve the vortex-induced drag characteristics, adoption of a polyhedral wingtip device such as in a C-wing morphology leads itself to penalties in other technical fields, especially when it concerns structural and aero-elastic considerations. Generally speaking, the requirements for minimum vortex-induced drag and minimum structural weight are diametrically opposed. In order to minimize the vortex-induced drag, the wing system must have either a large lateral, or, a large vertical dimension, usually leading to a heavy structure. Viscous effects and additional structural weight are two aspects of wing extension designs, which must be carefully taken into consideration during the initial design phase. Figure 2 (overleaf) presents an illustrative explanation of the mechanisms associated with C-Wing aerodynamics and provides a notion of lift distribution and extent of deformation during a 2.5g maximum symmetric manouevre condition.

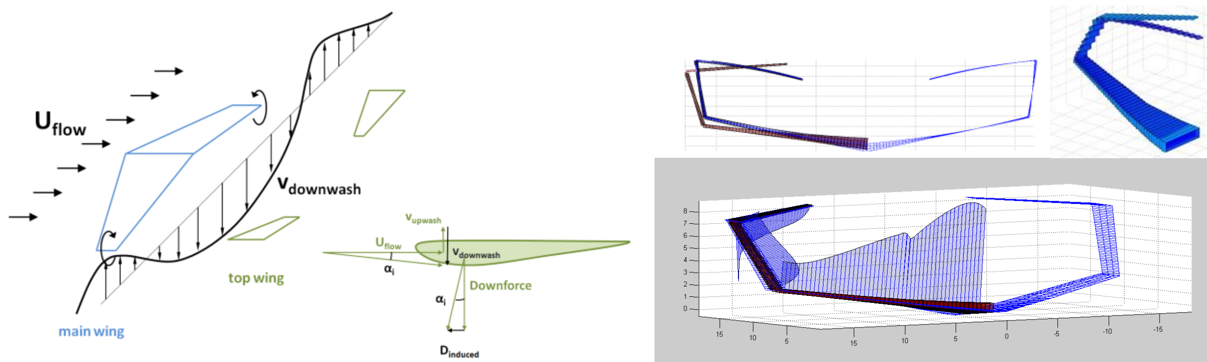


Figure 2: C-Wing aerodynamic characteristics: basic explanation of “thrusting effect” (left), and, lift distribution including extent of deformation during symmetric 2.5g manouvres

The Self-Trimming Wing

As was established previously, the unusual C-Wing layout of the aircraft aims at enhancing and optimising vehicular efficiency for all flight phases. The tailless aspect of this design implies that the whole wing system must be capable of guaranteeing satisfactory longitudinal stability and control relying only upon its non-planar, polyhedral surfaces. The Flight Control System (FCS) is divided into a Primary (PFCS) system, which caters for the pitch, roll and yaw control, and, a Secondary system comprising high-lift devices (flaps and slats on slave tracks) and spoilers. The Ce-Liner is to be control-configured with longitudinal, roll and lateral control accomplished via a full 6 DoFs Stability Augmentation System (SAS). This approach is posited to assist handling qualities and shall negate any questions on how the onboard pilot will react to a quasi-3-axes-coupled aircraft. For the PFCS, cross-coupling between pitch and roll is accomplished through an explicit inter-connect and implementation of advanced control allocation protocols. A cross-tie between roll and yaw has been adopted with intent to improve One-Engine Inoperative ground maneuvering and airborne operations as well as to enhance control authority during low-speed, cross-wind operations. The 3-axis SAS is to employ full envelope protection (aircraft orientation, speeds and loads) with no manual reversion.

Results of five flight cases considered for a preliminary assessment of the self-trim capability of the C-wing configuration, i.e. cruise, symmetric maximum manoeuvre, take-off rotation, landing de-rotation and go-around were studied by Trapani et al.[3]. For the latter three low-speed flight states investigations have shown that excessive and impractical TW incidence angles (between 16° and 28°) are required in order to lend sufficient trim authority. Thus was borne definition of a Self-Trimming Wing (STW) where adaptive utilities augment C-Wing functionalities, efficiency and authority for stability and control purposes.

Identifying Pertinent Adaptive Degrees-of-Freedom

The function of the STW is to provide static stability in pitch, trim for low-speed and high-speed operations, and, ensure control authority for critical cases like take-off rotation, de-rotation during landing and full-thrust go-around maneuvers. Assuming the influence of the vertical tail drag to pitch is small, the free-body diagram describing forces and moments contributing to longitudinal motion for all flight phases and manoeuvres is given in Fig. 3 (overleaf).

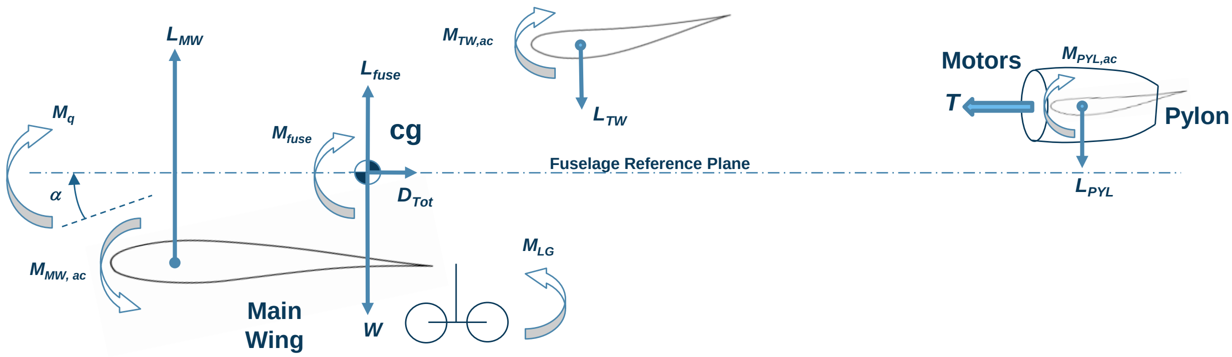


Figure 3: Forces and moments in pitch associated with Ce-Liner concept; clockwise (+) and up (+).

Analytically, for a given aircraft angle-of-attack, α, the pitching moment equation about the centre-of-gravity (cg) of the aircraft in coefficient form becomes:

$$\boldsymbol{C_{m,CG}} = \boldsymbol{C_{mo,WFNP}} + \boldsymbol{C_{m,MW}} + \boldsymbol{C_{m,TW}} + \boldsymbol{C_{m,T}} + \boldsymbol{C_{m,LG}} + \boldsymbol{C_{m,q}} \tag{1}$$

where $C_{m,CG}$ is the total pitching moments about the aircraft cg, $C_{mo,WFNP}$ represents the zero-lift pitching moment of the wing-fuselage-nacelles-pylons, $C_{m,MW}$ is the moments generated by the MW, $C_{m,TW}$ denotes contribution by the TW, $C_{m,T}$ signifies thrust influence about the cg, $C_{m,LG}$ the pitching moment contribution of the landing gear, and, $C_{m,q}$ the pitching moment due to pitch rate.

Upon scrutinisation of $C_{m,MW}$, a contribution due to the pitching moment gradient with respect to α is $C_{m\alpha,MW}$, contribution from ailerons is given by $C_{m,ail}$, the parameter $C_{m,flap}$ represents pitching moments from leading and trailing edge high-lift device deployment, and, $C_{m,spoil}$ is the pitching moments produced by spoilers. This decomposition produces the following equation

$$\boldsymbol{C_{m,MW}} = \boldsymbol{C_{m\alpha,MW}}\left(\boldsymbol{\alpha} + \boldsymbol{i_{MW}} - \boldsymbol{\alpha_{o,MW}}\right) + \boldsymbol{C_{m,ail,MW}} + \boldsymbol{C_{m,flp,MW}} + \boldsymbol{C_{m,spl,MW}} \tag{2}$$

Assuming the TW acts as a variable incidence, flapped surface (akin to a stabilator device) and allowing for additional DoFs, thus permitting scope for aerodynamic adaption, $C_{m,TW}$ could be decomposed into

$$\boldsymbol{C_{m,TW}} = \boldsymbol{C_{m\alpha,TW}}\left(\boldsymbol{\alpha} + \boldsymbol{i_{TW}} - \boldsymbol{\alpha_{o,TW}} - \boldsymbol{\varepsilon_{\alpha,TW}}\right) + \boldsymbol{C_{m,flp,TW}} + \boldsymbol{C_{m,adp,TW}} \tag{3}$$

where i and α_o represent the local surface incidence angle with respect to the fuselage reference plane, and, zero-lift α, respectively. The parameter $\varepsilon_{\alpha,TW}$ recognizes the downwash angle seen at the TW due to the MW. Upon consideration of possibilities for adaption, $C_{m,adp,TW}$, is elaborated as

$$\boldsymbol{C_{m,adp,TW}} = \boldsymbol{C_{m,TWcam}} + \boldsymbol{C_{m,TWtwt}} + \boldsymbol{C_{m,TWswp}} + \boldsymbol{C_{m,TWstg}} + \boldsymbol{C_{m,TWgap}} + \boldsymbol{C_{m,TWcnt}} \tag{4}$$

Here, subscripts *cam* = camber, *twt* = twist, *swp* =sweep, *stg* = stagger with respect to the MW, *gap* = vertical height with respect to the MW, and, *cnt* = cant angle, all applicable to the TW planform.

Upon examination of the DoFs sensitivies produced by each constituent and combinations therein, these were traded against each other due to consideration of mechanistic complexity and weight. It was concluded that manipulation of camber and twist would best complement the stabilator-type functionality.

Integrated Design of the Adaptive Top-Wing

The TW lifting surface design is a variable stiffness, adaptive structural system comprising embedded specially designed antagonistic electro-strictive actuators within a variable geometry truss arrangement employing a combination of flexural and articulated joints. The trailing edge discrete surface of the TW is actuated via two-way electro-mechanical actuators installed on each lifting surface wing to augment control and ensure system redundancy.

Top-Wing General Design Description

As depicted in Fig. 4 the TW is an all-moving surface with plain trailing edge flap, i.e. akin to a stabilator. Also, it is designed as an active poly-morphing device that can deliver two additional DoFs to that of the stabilator-like function. Variable incidence angle schedules of 2° TED (trailing-edge down) and 3° TEU (trailing-edge up) are achieved using an electrically powered rotary actuator driving a jackscrew acting at the forward partition of the primary spar. In addition to providing variable incidence, adaptive positive direct-camber, and still under investigation, variable in-direct-twist (wash-out) via spanwise differential camber DoFs are to be facilitated. The presence of the discrete, flapped surfaces with a deflection range of ±25° has been incorporated in order to cater for high-bandwidth effector actuation.

Analysis has highlighted camber schedules of less than or equal to 3.5% result in a dead-band of response. In other words, a camber schedule of less than 3.5% does not generate any significant incremental moment for purposes of vehicle trim or control power, and tends to penalize the overall wing system aerodynamic performance. This circumstance is attributable to the complex nature of localized aerodynamic loading for C-Wing morphologies. A soft-stop maximum camber for en route only use is set at 5.0%, whereas, a hard-stop maximum camber of 8.0% is available. In normal mode, the camber change rate is designed to be 7.50 deg/s (0.131 rad/s), or alternatively, 5.6% camber change per second (cps), i.e. a change from the datum (1.0% camber) to the low-speed maximum camber of 8.0% is predicted to take 1.3 s, and, change from the datum (1.0% camber) to the maximum en route camber of 5.0% is predicted to take 0.7 s. In an abnormal mode, where performance degradation of camber scheduling occurs due to a failed set of actuators, the camber change rate is designed to be 3.50 deg/s (0.061 rad/s), or alternatively, 2.6% cps, i.e. a change from the datum (1.0% camber) to the low-speed maximum camber of 8.0% is predicted to take 2.7 s, and, change from the datum to the maximum en route camber of 5.0% is predicted to take 1.5 s.

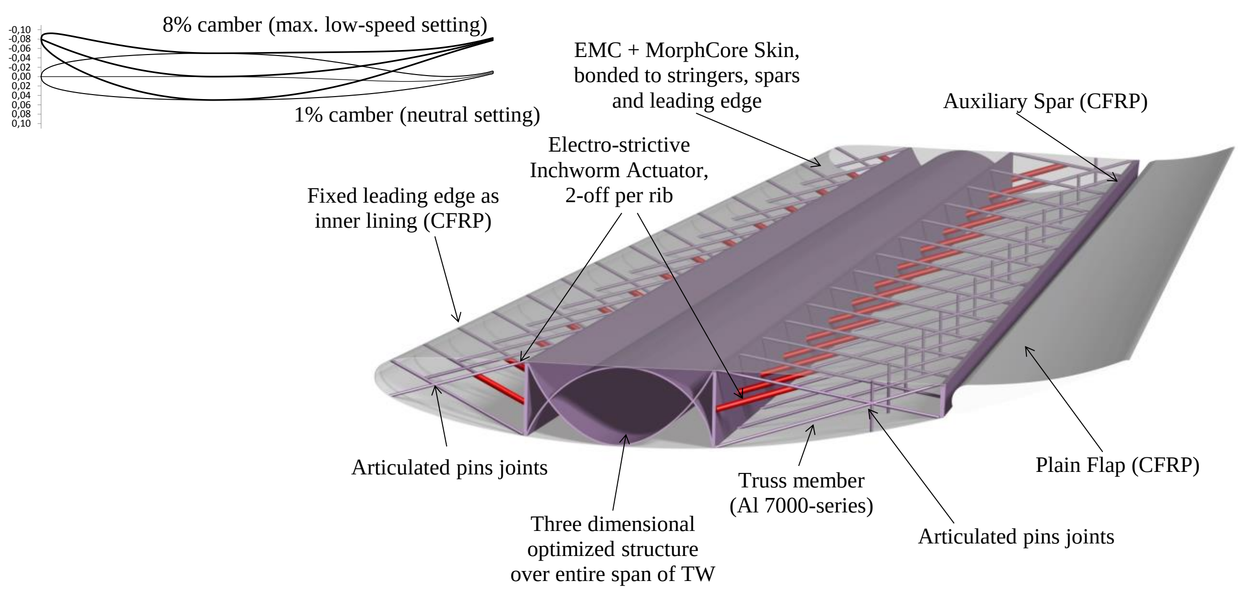


Figure 4: Schematic illustration of the adaptive Top-Wing design of the Ce-Liner.

Top-Wing Structural Design

The proposed structural concept comprises a single beam where the forward main spar is located at 20% local chord (c) and the rear spar is located at 45%c. The loss of rigidity of having the rear spar relatively close to the front spar is encountered by filling the space between the two spars and over the complete span of the TW with an optimized three dimensional structure. As the the EIS of the Ce-Liner is projected for 2035 this optimized structure could be manufactured as momolithic piece using additive layer manufacturing techniques. First estimations show that this approach provides sufficient torsional and bending stiffness to the TW. Since the Ce-Liner is equipped with a purely electric propulsion system there is no need to accommodate fuel tanks in the TW. Therefore, this space can be filled with such a stiffened structure.

An auxiliary rear spar that supports the plain flapped elevator hinge is located at 75%c. The spars as well as the fixed leading edge are made of Carbon Fibre Reinforced Polymer (CFRP). Stringers attached to fixed joints running along the periphery of each rib are made of Al 7000-series and serve to reinforce the structural layout of the TW further.

The upper and lower flexible skins forming the surface of the TW are to be made of a sandwich arrangement comprising a pre-tensioned Polyurethane Elastomeric Matrix Composite (EMC) with carbon fibres[4] covers reinforced by a cellular core designated as MorphCore[5]. This approach produces a skin surface with relatively low stiffness in a chordwise direction, and hence, allows for reduction of necessary actuator forces. Another approach is to adopt an EMC skin and conventional hexagonal honeycomb sandwich. The benefit would be an ability of this skin combination to resist a modest amount of bending loads. An engineering trade-study is currently underway in establishing the feasibility of this alternative.

The articulated truss ribs (14-off) in addition to defining the shape of the airfoil distribute the aerodynamic pressure loads as well as concentrated loads. Each variable camber rib truss assembly consists of 8 truss members (Al 7000-series), 2 articulated pin points, 4 flexible or compliant joints and, 2 electro-strictive actuators. Through a spacing of 610 mm the articulated truss ribs also aid in preventing buckling by restricting the free column length. Importantly, the articulated truss ribs accommodate each adaptive hybrid-compliant sub-system, thus allowing direct-camber and possibly in-direct-twist DoFs. The articulated truss ribs also provide a surface for bonding the EMC skin and MorphCore sandwich. Once outfitted, the EMC plus MorphCore sandwich is expected to have a maximum strain of 3.2% (corresponding to an 8% camber schedule) on the lower surface and the minor-to-modest negative strains (up to -0.6%) on the upper surface are envisaged to be avoided through pre-tensioning. Stringers of Al 7000-series, run the entire length of the TW span and apart from its structural mechanical (resisting failures due to buckling) role also serve as an interface for each rib.

Actuator Power Requirements

There are many different approaches for the actuation system, for example shape memory alloys[6]. However, in case of this work the application of antagonistic electro-strictive actuators were deemed appropriate for the TW variable geometry truss design. The final choice was an electro-strictive Inchworm actuator of the type proposed by Suleman et al.[7] Such Inchworm actuators use small incremental steps in order to produce large displacements. Incremental steps are achieved via a “walking” mechanism consisting of two flextensional brake assemblies separated by a centre electro-strictive stack. Each brake assembly is forced to clamp and unclamp according to a particular sequence in order to invoke actuator motion. When the stacks are de-energised, the frames grip the outer casing, thus locking the actuator in place. This approach has an advantage of maintaining a locked position with no electrical power. On-going work using energy-based formulations is focusing on maximising mechanical efficiency or geometric advantage whilst delivering requsite kinematic motion and ensuring a sufficient amount of stiffness against external loads. Currently, a multi-criteria formulation of the Mutual Potential and Strain Energy approach as expounded by Frecker[8] is being utilised in designing a variable geometry and variable stiffness truss structure. Most recent estimates show that the maximum power required by a single actuator is up to 25 kW. With an assumed power density of 11kW/kg as of similar actuator types[9], the estimated weight of one actuator is 2.5kg. Figure 5 (overleaf) shows a first force versus time history chart. The actuation time is 1.5s from the datum to maximum en route camber of 5.0%, see above.

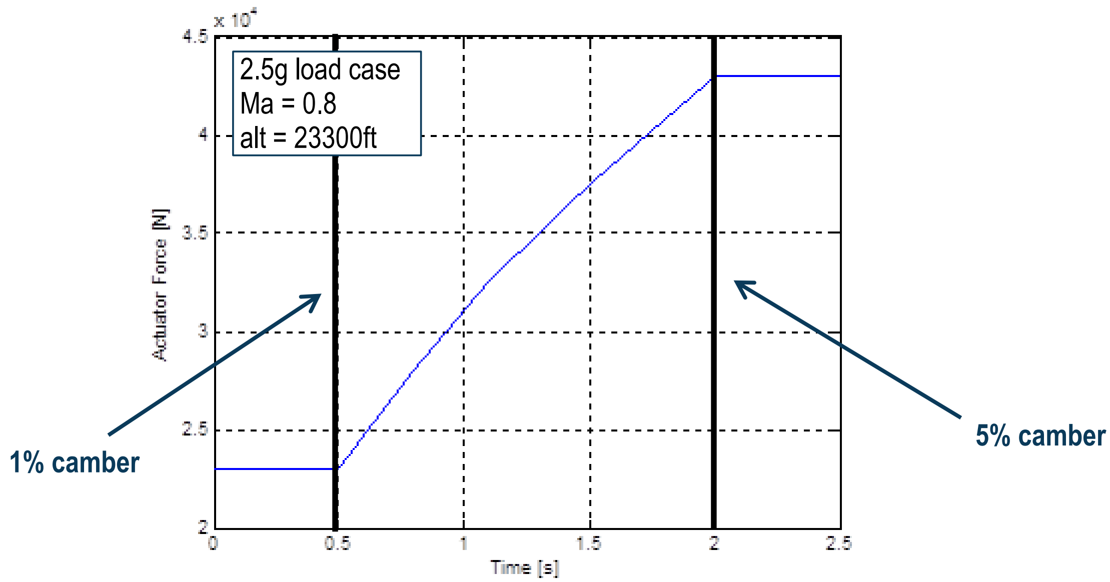


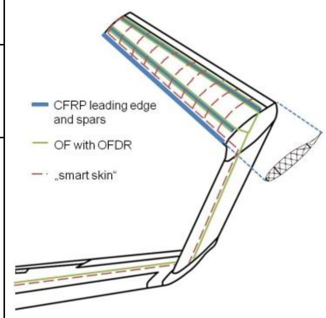
Figure 5: Force vs. time history chart for actuation force for one actuator

Multi-functionality Benefits and Potential

In principle, gust load alleviation, together with manouevre load and flutter mode control techniques could be implemented in an adaptive STW system. Extending beyond these, opportunities also arise for operational and lifetime SHM with express purpose of providing guidance for maintenance scheduling as well as actuation monitoring (position and rates). The benefit of such a combined system is that undesirable aero-elastic deformations from manoeuvring loads (picked up by the SHM system) may provide feedback to the FCS thereafter issuing active adaption commands in order to minimize stress on the wing system.

A special purpose SHM and shape supervision system for the Ce-Liner wing system has been proposed by Lorenz et al.[10] and the basic layout of the hybrid sensing system together with some preliminary specifications for the structure of the adaptive TW is shown in Table 1 (overleaf). For the spar structure Optical Frequency Domain Reflectometry (OFDR) glass fiber sensing was taken to be a good option for spanwise bending and torsion monitoring purposes because the chosen CFRP and silica-based Optic Fibre (OF) have compatible elastic strain limits. Differential strain measurements between parallel sensing fibers along the spar surfaces allow supervision of adaption-induced and aeroelastics-induced twist as well as bending in the spanwise direction. It is anticipated that accumulated statistical CFRP fatigue data by the time of EIS 2035 will be sufficiently comprehensive such that less stringent material safety margins, and ultimately a lighter spar design could be procured. In the construction of each of the twelve TW variable geometry articulated truss ribs, the trusses carry minor loads and are not exposed to high stresses. In view of this, passive surveillance can be performed by monitoring the electric power requirement of the actuators on each rib: if a truss at a given location fails, power loads of the five rib-wise Inchworm actuators will change in a characteristically recognisable fashion. The EMC skin is to include “smart” sensing, e.g. by embedding carbon nanotubes[11], which is postulated to also serve in helping to modestly reinforce the elastomer in a chordwise direction. In this way, parallel conductive channels with strain-dependent and pressure-dependent electrical resistance can be realised in the material. This offers the prospect for both strain measurements in the surface and impact detection at the leading edge, if changes in the electrical impedance are mapped along the surface over time by, for example, electrical impedance tomography. This concept is analogous to “smart-skin” or “E-skin” approaches from robotics[12].

Table 1: Adaptive Top-Wing bill-of-material and sensing system characteristics[10].

Morphing Top-Wing Component	Target Material Strain or Torsion or Power	Candidate Material	Sensing System Characteristics
Skins	-0.6% upper surface +3.2% lower surface	Polyurethane EMC plus MorphCore sandwich	
Rib Truss Members and Fixed/Pin Joints	N/A	Al 7000-series	
Rib Truss Flexural Joints	0.75 rad	Polyurethane EMC	
Rib Truss Actuators	0.057% per stack element, max. 160 W per actuator	Inchworm type, stacks made of electro-strictive material	
Stringers	0.17 rad (rel. to 50%c span)	Al 7000-series	
Main Spar and	0.16 rad (rel. to root)	CFRP	
Rear Spar		CFRP	
Auxiliary Spar	0.12 (rel. to root)	CFRP	

Simplified Bill-of-Material Weight Estimation

The in-house developed structures analysis tool dAEDalus (see Seywald[13] and Eisenbarth[14]) allowing for non-linear geometric deformation in bending and so-called follower aerodynamic loads was utilized for the wing box weight estimation. The TORNADO vortex lattice code produced by Melin[15] has been employed when predicting aerodynamic forces for given flight state and aircraft configuration. Critical load conditions covering maximum symmetric manoeurvre and buckling have been taken into consideration. According to overall aircraft performance targets defined for Ce-Liner, the total STW weight was estimated in previous studies to be around 11000 kg[16]. However, studies conducted for the this paper showed an increased weight for the entire wing of 12100kg for a typical spar and rib layout. The difference to the older studies is the used Prandtl-Glauert Correction used in the aerodynamic calcualtions. As mentioned above thr proposed TW central structure uses an optimized internal structure. Therefore, the weight of the TW can be significantly reduced, which saves around 450kg. Thus, the STW weight is estimated to be 11660kg.

Conclusion

In this paper the concept of an Self-Trimming C-Wing for a future Universally Electric Aircraft, the Bauhuas Luftfahrt Ce-Liner, is presented. The working principle of the C-Wing is explained, since in this case it serves not only as a measure for drag reduction, but also to provide longitudinal stability. A preliminary design of the Top-Wing part of the C-Wing is introduced with an adaptive device to further enhance controllability of the aircraft.

The structural part of the Top-Wing is proposed to consitst of an optimized three dimensional structure and several section of rib trusses. Due to the actuation of the trusses the camber of the Top-Wing can be altered.With this additional degree of freedom the controllability of the longitudinal attitude of the Ce-Liner is increased further.

A first estimation of the needed maximum power of each actuator is 25kW with a total number of 28 actuators and the weight of the C-Wing is estimated to be 11660kg.

Acknowledgement

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References

1. Barbarino, S., Saavedra Flores, E., Ajaj, R.M., Dayyani, I. and Friswell, M.I. (2014) A review on shape memory alloys with applications to morphing aircraft. Smart Materials and Structures, 23, (6), 063001.
2. Bauhaus Luftfahrt, Visionary Aircraft Concepts Group, “Concept 002: Initial Technical Assessment of an Electrically-Powered, Medium-Capacity, Short-Haul Transport Aircraft”, Internal Report IB-12021, Bauhaus Luftfahrt e.V., 2012.
3. Trapani, M, Pleissner, M. Isikveren, AT, Wieczorek, K, “Preliminary Investigation of a Self-trimming Non-planar Wing using Adaptive Utilities”, Paper 1316, 61. Deutscher Luft- und Raumfahrtkongress, Berlin, Germany, September 2012.
4. Bubert, E.A., Woods, B.K.S., Lee, K., Kothera, C.S., and Wereley, N.M., 2010, “Design and Fabrication of a Passive 1D Morphing Aircraft Skin”, Journal of Intelligent Material Systems and Structures, 21(17): 1699-1717. DOI: 10.1177/1045389X10378777.
5. Kothera, C.S., Woods, B.K.S., Bubert, E.A., Wereley, N.M., and Chen, P.C., “Cellular Support Structures used for Controlled Actuation of Fluid Contact Surfaces,” US Patent No. 7,931,240, Techno-Sciences, Inc., Beltsville, MD, issued on Apr. 26, 2011.
6. Barbarino, S., Bilgen, O., Ajaj, R.M., Friswell, M.I. and Inman, D.J. (2011) A review of morphing aircraft. Journal of Intelligent Material Systems and Structures, 22, (9), 823-877.
7. Suleman, A., Burns, S., Waechter, D., “Design and Modelling of an Electrostrictive Inchworm Actuator”, Pages 567–586, Volume 14, Issue 5, Mechatronics, June 2004.
8. Frecker, M., “Optimal Design of Compliant Mechanisms”, Doctor of Philosophy in M.E., The University of Michigan, 1997.
9. Huber, J. E., Fleck, N. A., Ashby, M. F., “The selection of mechanical actuators based on performance indices”, Proceedings of the Royal Society London A, 1997.
10. Lorenz, L.C., Büchter, K.-D., Boegler, O., Kling, U. Isikveren, A.T., “Structural Health Monitoring as an Enabling Technology for Active Compliant Systems”, 9th International Workshop on Structural Health Monitoring, Stanford, California, September 10-12, 2013.
11. Raghavan, A. et al. 2009. “Structural Health Monitoring using Carbon Nanotube (CNT) Enhanced Composites,” 7th International Workshop on Structural Health Monitoring, Stanford, California, September 9-11, 2009.
12. Loyola, B. et al., “Detection of Spatially Distributed Damage in Fiber-Reinforced Polymer Composites,” Structural Health Monitoring, 12(2), 2013.
13. Seywald, K., “Wingbox Mass Prediction considering Quasi-Static Nonlinear Aeroelasticity”, Report LS-DA 11/09-EX, Master of Science Thesis, Institute of Aircraft Design, Technische Universität München, January 2012.
14. Eisenbarth, D., “Elastic Instability Analysis and Integration for a Non-Linear Structural Design Tool”, Term Paper, Institute of Aircraft Design, Technische Universität München, May 2013.
15. Melin, T., “A Vortex Lattice MATLAB Implementation for Linear Aerodynamic Wing Applications”, Masters Thesis, Royal Institute of Technology (KTH), Department of Aeronautics, Sweden, 2000.
16. Kling, U., Gologan, C., Isikveren, A. T., Hornung, M., “Aeroelastic Investigations of a Self-Trimming Non-Planar Wing”, 62. Deutscher Luft- und Raumfahrtkongress, Stuttgart, Germany, September 2013.