AEROELASTIC INVESTIGATIONS OF A SELF-TRIMMING NON-PLANAR WING

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Abstract

Taking a step beyond conventional aircraft layouts, aerodynamic efficiency may be improved to a significant degree by the adoption of radical new wing designs. One such approach is the non-planar C-wing (CW), as exemplified by the “Ce-Liner”, a so-called universally electric aircraft concept unveiled by Bauhaus Luftfahrt in 2012. One of the interesting features of the Ce-Liner non-planar CW configuration is a longitudinal control power and self-trimming capability via a stabilator-like function of the Top-Wing (TW) panel incorporated because of the absence of a horizontal tail. In this work an aero-elastic examination of the CW configuration is presented in order to demonstrate this self-trimming capability under consideration of vortex-induced drag reduction and weight impact compared to an equivalent, conventional in-plane reference wing (RW). The aero-structural characteristics of the wing were predicted using a well-known low-fidelity code based upon the Vortex Lattice Method coupled to a simplified non-linear finite element beam model. Both 1.0g, steady, level cruise and 2.5g symmetric pull-up cases for different TW incidence angles are presented. Results have shown that typical cruise can be accommodated in terms of sufficient trim authority, however, for the 2.5g load case the most aft center-of-gravity allowable was approximately 14% Mean Aerodynamic Chord short of the maximum aft required with respect to loadability considerations. Direct and equitable comparisons between the RW plus stabilizer combination and CW found a 14.9% reduction in vortex-induced drag, favorable to the CW. Similarly, this produced an aircraft-level drag reduction of 6.8%. In addition, the estimated mass difference between RW plus stabilizer combination and CW resulted in the CW having a 3.9% penalty.

1. NOMENCLATURE

Acronyms

ACARE	*Advisory Council for Aviation and Innovation in Europe*
BHL	*Bauhaus Luftfahrt*
CFRP	*Carbon Fiber Reinforced Plastic*
CG	*Center of Gravity*
COS	*Coordinate System*
CW	*C-Wing*
dof	*Degree of Freedom*
EIS	*Entry Into Service*
FCS	*Flight Control System*
MAC	*Mean Aerodynamic Chord*
MTOW	*Maximum Take-Off Weight*
MW	*Main Wing*
PAX	*Passenger*
PFCS	*Primary Flight Control System*
RW	*Reference Wing*
SAS	*Stability Augmentation System*
STW	*Self-Trimming Wing*
SW	*Side Wing*
TED	*Trailing Edge Down*
TEU	*Trailing Edge Up*
TW	*Top Wing*
VLM	*Vortex Lattice Method*

Symbols

C	*Aerodynamic coefficient*
L	*Lift (N)*
M	*Moment (Nm)*
m	*mass (kg)*
S	*Wing area (m²)*
T	*Thrust (N)*
X	*x-coordinate (m)*

Subscripts and Indices

comb	*Combination*
Di	*Vortex-induced drag*
FPN	*Fuselage + Pylon + Nacelle*
fuse	*Fuselage*
LG	*Landing Gear*
m	*Pitching moment*
min	*Minimum*
nac	*Nacelle*
PYL	*Pylon*
q	*Pitch rate*
ref	*Reference*
Stab	*Stabilizer*
sys	*Flight control systems and secondary structures*
T	*Instantaneous Thrust*
Tot	*Total*

2. INTRODUCTION

The Advisory Council for Aviation and Innovation in Europe (ACARE) defined within its research program Flightpath 2050 [1] ambitious goals to significantly reduce the environmental impact of aircraft. A CO_2 reduction target of 68% for the aircraft airframe and propulsion system are defined in the Strategic Research and Innovation Agenda [2].

In 2012, Bauhaus Luftfahrt (BHL) unveiled the Ce-Liner, a conceptual study of a Universally-Electric Systems Architecture aircraft including electric propulsion powered by batteries [3] (see Figure 1, overleaf). Advanced Li-ion batteries are used to operate the fuselage-mounted electric fans and to provide thrust to the aircraft with a Maximum Take-Off Weight (MTOW) of 109.3 tons. The Ce-Liner is a passenger aircraft with a maximum capacity of 189 PAX, a wing span of 36.0 m and a design range of 900 nm (1667 km). Its expected entry into service (EIS) is 2035.

To fulfill the span limitation constraints of the International Civil Aviation Organization Annex 14 Code C for aerodromes practices and concurrently being able to produce enough lift to compensate the high weight of the installed batteries a Self-Trimming Wing (STW) was designed. This design increases the aerodynamic efficiency and reduces the wing systems weight, since a stabilizer is omitted.

As described in FIG 1, the C-wing (CW) consists of a Main-wing (MW), a side-wing (SW) and a Top-wing (TW). The TW was designed from the outset as a stabilator-like device in order to control the longitudinal attitude of the aircraft.

FIG 1 Bauhaus Luftfahrt Ce-Liner with C-Wing [3].

In Ref. [4] a first study was presented and several degrees of freedom of the TW were proposed to be able to control the pitching movement of the Ce-Liner in different flight phases. However, in this first study the wing was considered to be rigid and no deformations with respect to aero-elastic effects were taken into account.

In the work presented a preliminary study of the aero-elastic effects on the STW is carried out. Therefore, the Vortex Lattice Method (VLM) is coupled with a finite element beam model to simulate the aero-elastic behavior of the STW. The wing structure is sized to withstand the maximum loads for the 2.5g maneuver case, while the lift distribution is optimized to minimize the vortex-induced drag in the 1.0g cruise state. The pitching moment coefficient is used as measure to examine if a trimmed flight state for different center of gravity (CG) positions can be achieved in 1.0g flight level cruise and for the 2.5g maneuver case. The optimized vortex-induced drag of the STW is compared to the optimized vortex-induced drag of a conventional wing and stabilizer configuration.

3. C-WINGS AND BASELINE AIRCRAFT

Here, an introduction to CW aerodynamic attributes are presented. This is followed by a basic description of the STW design, specifically, the Flight Control System (FCS) functionality including some cursory information about stabilator characteristics. To round off this section, pertinent data about the Ce-Liner and corresponding flight conditions necessary for the upcoming aero-elastic trim study is reviewed.

3.1. Brief Overview of C-Wings

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 tendency 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 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 flow-field 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 CW 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.

3.2. Self-Trimming Wing Design Description

As was established previously, the unusual CW layout of the aircraft aims at enhancing and optimizing 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 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 degrees-of-freedom (dof) 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

As depicted in FIG 1 (previous page) the TW is an all-moving surface with plain trailing edge flap, i.e. akin to a stabilator. Variable incidence angle schedules of 2.0° TED and 13.0° TEU are achieved using an electrically powered rotary actuator driving a jackscrew acting at the front spar. The presence of discrete, flapped surfaces with a deflection range of ±25° has been incorporated in order to cater for high-bandwidth effector actuation.

3.3. Ce-Liner Data and Reference Flight State

The Ce-liner is fully powered by advanced batteries stored in the fuselage. Therefore, no fuel is needed and the CG can be assumed to not change significantly during en route operations. However, by changing the positions of the batteries and/or varying the number of carried batteries or the payload, a CG variation has still to be considered for longitudinal trim.

In TAB 1 the main data of the Ce-Liner relevant for the studies in this paper is summarized.

TAB 1 Flight condition information used in aero-elastic trim study.

Operational Condition	State Parameter	Value
	MTOW	109300 kg
Cruise	Speed	M0.75
	Altitude	33000 ft
2.5g Maneuver, Cruise Conditions	Speed	M0.75
	Altitude	33000 ft
2.5g Maneuver, Max Dynamic Pressure	Speed	M0.80
	Altitude	23300 ft

4. ANALYTICAL PROBLEM FORMULATION AND NUMERICAL METHODS

This section reviews the basic array of equations necessary for analysis of longitudinal trim, and, provides an overview of the high-end, low-fidelity numerical methods used for aero-elastics.

4.1. Trim Function

In order to provide a trimmed flight state around the pitching axis of an aircraft the moments taken around the CG of the entire aircraft should be zero. Therefore, all components of the aircraft, which produce lift and drag have to be considered. For this work the pitching moment coefficients of the considered wings, fuselage, pylons, nacelles and also the thrust of the engines of the Ce-Liner are taken into account. The schematic sketch in FIG 2 shows the considered moments in case of the Ce-Liner.

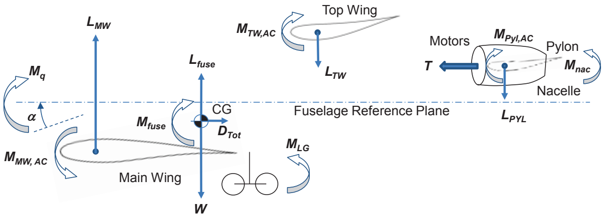

FIG 2 Forces and moments in pitch associated with Ce-Liner concept; clockwise (+) and up (+).

Disregarding the landing gear and assuming a pitch rate of zero, the total pitching moment with respect to CG ($C_{m,CG}$) can be expressed as follows

$$C_{m,CG} = C_{m,MW} + C_{m,TW} + C_{m,T} + C_{m,FPN} \qquad (3.1)$$

where $C_{m,MW}$ is the pitching moment of the MW, $C_{m,TW}$ is the pitching moment coefficient generated by the TW, $C_{m,T}$ and is the pitching moment coefficient due to the thrust of the engines, $C_{m,FPN}$ is the pitching moment coefficient of the fuselage, pylons and nacelles. From this follows that the TW has to produce a down force in order to balance the pitching moments produced by the different components. Note that the pylon is assumed to be passively tailored in order to provide a means of trim augmentation for the TW.

In case of the in-plane reference wing, which is a standard configuration of the MW of the CW with a stabilizer, the pitching moment coefficient about the CG is

$$C_{m,CG} = C_{m,MW} + C_{m,Stab} + C_{m,Comp} \qquad (3.2)$$

where, $C_{m,Stab}$ is the pitching moment coefficient of the stabilizer and $C_{m,Comp}$ is the summation of pitching moment coefficients attributable to the fuselage, nacelles, pylons and instantaneous thrust.

4.2. Wingbox Sizing Methodology

The wingbox, the structural part of the wing of an aircraft, which carries the biggest part of the loads, has to withstand different load cases, such as gust loads and aileron roll loads. In the work presented only the 2.5g load case is taken into account. The wingbox of the STW and the RW are sized to withstand the 2.5g load case.

A wingbox mass prediction method was developed at the Bauhaus Luftfahrt using the numerical computing environment MATLAB© [5]. This structures analysis tool called dAEDalus allows for non-linear geometric deformation in bending and applies so-called follower aerodynamic loads. Critical load conditions covering maximum symmetric maneuver, gust, aileron maneuver and buckling are taken into consideration. The method sizes the thicknesses of the skin, front and rear spar of a given wing geometry according to the applied aerodynamic forces and assumed material properties. In the sizing iteration loop the buckling analysis inserts stringers to the cross sections of the beam elements [6]. The ribs, flight controls and secondary structures, which are situated in a wing are included with empirical methods [7]. The weight of the ribs depends on the density of the used material. The weight of the flight controls and the secondary structures are linearly distributed over the wing span and are estimated to be 45% of the entire wing mass. The wingbox mass with all additional masses defines the inertia release of the wing and decreases the aerodynamic loads. In this paper, the mass breakdown of the wing is defined as follows:

$$m_{wing} = m_{wingbox} + m_{ribs} + m_{sys} \tag{3.3}$$

The method uses the VLM tool “TORNADO” [8] to calculate the aerodynamic forces. The magnitude of the aerodynamic forces is calculated in that manner that for a given MTOW of a considered aircraft and wing geometry enough lift has to be produced. The aerodynamic model is adopted within each iteration to the deformations of the structural model and new aerodynamic forces are calculated. This results again in new deformations and in a change in the estimated wingbox weight. The solver algorithm stops when a quasi-static equilibrium is reached. In the self-design iteration process of the wingbox the thicknesses of the spars and the skin are adopted in each spanwise section to the applied local loads and are dimensioned to not exceed the maximum yield strength (plus design factor) of the specified material.

This procedure can be repeated for different critical load cases. If the different load cases result in different wingbox thicknesses for the spars and the skin, the design for the highest load is applied. However, in this study only the 2.5g load case is used as critical load case.

A simple wingbox definition is fitted into the shape of the airfoil used for the aerodynamic calculations (see FIG 1). The position of the front and rear spar is specified. With the spar positions the resulting height of the wingbox is calculated.

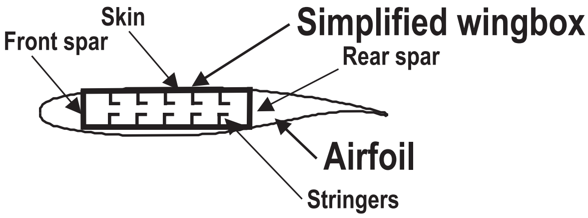

FIG 1 Simplified representation of the wingbox for numerical analysis purposes.

In FIG 4 the wingbox and the corresponding TORNADO model is shown. The rectangular cross section of the wingbox can be seen and the position of the wingbox with respect to the aerodynamic Tornado model of the wing.

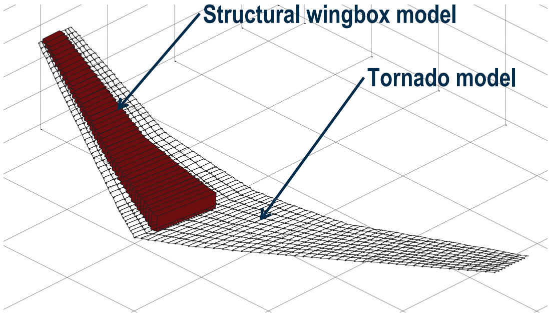

FIG 4 Example for calculated wingbox with TORNADO model of wing

4.3. C-Wing Trim Including Aero-elastic Effects

The purpose of the Ce-Liner CW is not only to reduce the vortex-induced drag, but also to serve as trim device. In the work presented the incidence angle of the TW is examined as degree of freedom for longitudinal trim.

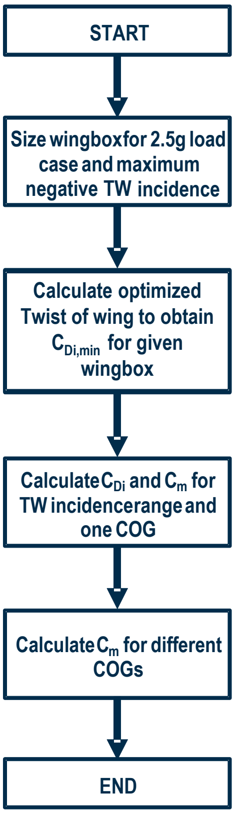

FIG 5 Used methodology for TW trim case studies.

To examine the influence of the TW incidence angle on the vortex-induced drag and the pitching moment coefficient the methodology displayed in FIG above was applied. First, a wingbox is sized for the 2.5g load case. Afterwards the twist of the CW was optimized to obtain the minimal vortex-induced drag, $C_{Di,min}$, considering aero-elasticity of of the designed wingbox. Then the C_{Di} for different TW incidence angles and one CG position was calculated. The last step was the calculation of C_m for different CG positions and different TW incidence angles to examine the CG range that can be trimmed for the given TW incidence anglesThe RW, which is set up to compare the results of the CW, see Section 5.1, is dimensioned using the same methodology as for the CW.

Since there is no TW incidence angle to vary, the RW was sized for the 2.5g load case under consideration of additional lift that the conventional wing has to produce due to the down-force of the stabilizer. Afterwards, the twist of the RW was optimized considering aero-elasticity to obtain the minimal vortex-induced drag design.

5. WING DEFINITIONS

This section is devoted to introducing the geometric conventions adopted for both the RW (plus stabilizer combination) and CW layouts. Also, the physical dimensions for both sets of wings with accompanying reference parameters are provided.

5.1. Reference Wing

The RW is a conventional wing designed with the same methodology as the STW, see Section 4. The RW corresponds to a modified MW of the considered CW. The modification consists of an increased span from 34.0 m to 36.0 m and a downscaling of the chord lengths to keep the wing area equal to the wing area of the MW of the CW. In contrast to the examined STW a stabilizer is needed to trim the aircraft. The stabilizer produces a down force and therefore, the wing has to produce a higher lift than actually required.

In FIG 66 the geometry of the wing as modeled in TORNADO is shown. The Mean Aerodynamic Chord (MAC) of the wing is displayed and also the Aerodynamic Center (AC) is marked. The aerodynamic properties of the reference wing are concluded in TAB 2. The reference area of the wing is 173.1m². This area serves also as reference area for the examined CW design.

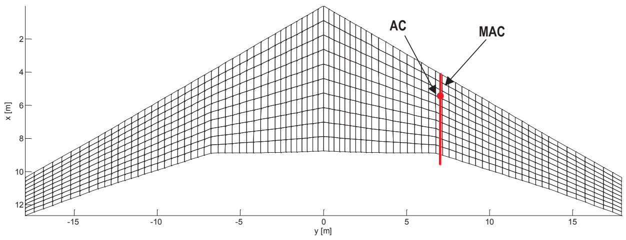

FIG 6 TORNADO model of the reference wing; MAC indicated.

TAB 2 Geometric properties of the Reference Wing.

Wing property	Unit	Value
MAC	m	5.5
X_{MAC} in local COS wing	m	4.0
Aspect Ratio (AR)	-	7.5
S_{ref}	m²	173.1
Span	m	36.0

The vortex-induced drag for the RW is calculated via TORNADO and for the stabilizer of the RW with the following equation [7]:

$$C_{Di,Stab} = \frac{1}{\pi e AR_{Stab}} C_{L,Stab}^2 \frac{S_{Stab}}{S_{ref}} \tag{3.4}$$

$C_{Di,Stab}$ is the vortex-induced drag of stabilizer, $C_{L,Stab}$ is the lift coefficient of the stabilizer, e is the wing span efficiency factor, AR_{Stab} is the Aspect Ratio of the stabilizer, S_{Stab} is the reference area of the stabilizer, and, S_{ref} is the reference area of the RW.

TAB 3 states the properties of the stabilizer, which is needed for the RW to trim the aircraft.

TAB 3 Assumed stabilizer properties.

Stabilizer property	Unit	Value
Mass	kg	590.0
Area	m²	30.3
Aspect Ratio (AR)	-	5.0
S_{Stab} / S_{ref}	-	0.175

5.2. Self-Trimming Wing

The STW can be divided into different sections: The (lower) MW is used to generate the needed lift. The TW serves as trim device and the SW, which is the connection between the MW and the TW.

In order to achieve minimum vortex-induced drag, the TW has to apply a down-force [9]. The idea of the STW of the BHL Ce-Liner is to use the down-force to control longitudinal stability and to trim the aircraft in the different flight phases. The schematic sketch of FIG 7 shows the lift force acting on the MW and the down force applied on the TW. The different incidences of the MW and the TW are also displayed. The sketch shows that the airfoil of the TW is carried out with a downward orientated pressure side to increase the produced down force.

In Ref. [4] different types of dof, such as variable camber, stagger and sweep, of the CW are introduced and established a full morphing solution to control the movement of the aircraft. In this case study only the incidence angle of the TW is considered as dof to control the longitudinal stability of the aircraft.

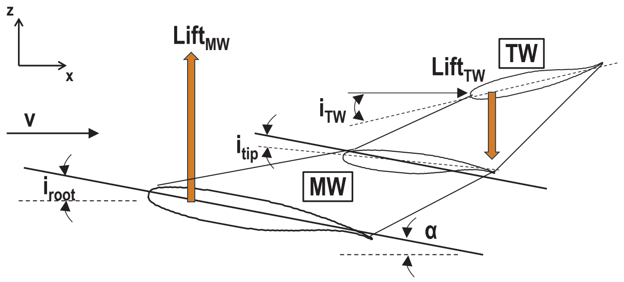

FIG 7 Schematic sketch of Self-Trimming C-Wing functioning

FIG 8 (overleaf) shows the TORNADO model of the CW. The MAC and AC of the complete CW and also the MAC of the MW are marked. It can be see that for the entire CW MAC and AC are moved aft.

The MAC of the CW is smaller than for the MW, due to the dimensions of the SW and TW. In TAB 4 the aerodynamic properties of the CW are concluded.

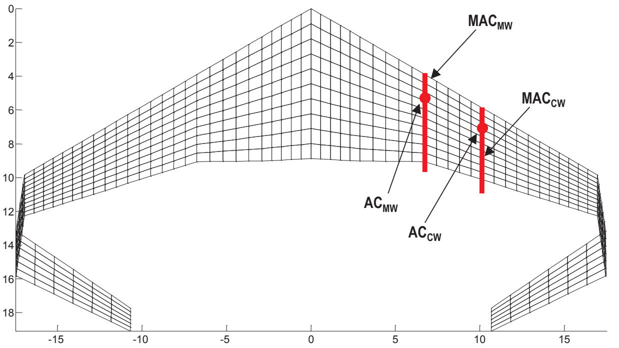

FIG 8 TORNADO model of the CW with MAC and MAC of the RW.

TAB 4 Geometric properties of the C-Wing.

Wing property	Unit	
MAC	m	5.08
X_{MAC} in local COS wing	m	5.85
Total Gross C-wing area	m²	214.7
S_{ref}	m²	173.1
Ratio CW wing area to reference area of RW	-	1.24

6. RESULTS

For the trim study the incidence angle of the TW of the CW was varied in a range of 2.0° TED and 13.0° TEU with respect to center fuselage plane of the Ce-Liner. The position of the aircraft CG was arbitrarily changed in a range between 5% MAC and 55% MAC. At the upper end of CG range this is taken to be the neutral point of the aircraft and beyond 55% MAC the configuration becomes statically unstable. The study was executed for both a 1.0g steady, level cruise flight condition, and, 2.5g symmetric pull-up maneuver. The 2.5g load case was assumed to take place at both typical cruise speed and level flight conditions, as well as at the flight envelope maximum dynamic pressure corner point.

6.1. Aero-elastic Trim Study

In FIG 9 the pitching moment coefficient for the different TW incidence angles and CG positions expressed in percentage of MAC are displayed for 1.0g steady, level flight conditions. It can be seen that due to the aerodynamic forces and the deflection of the wing the trimmable CG range is restricted. The most aft CG position that can be trimmed is around 44% MAC for a positive incidence angle of 2.0° TED. The most forward CG position that can be trimmed is 15% MAC for a negative incidence angle of 13.0° TEU. For the CG position of 35% MAC, which is the typical operational CG position of the Ce-Liner, the TW incidence angle is 2.0° TEU. This result compares favorably with an earlier study performed in Ref. [4] where an incidence angle of 1.0° TEU was obtained but assuming rigid wing characteristics.

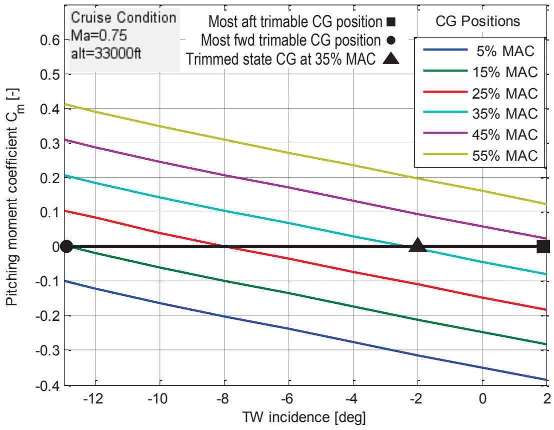

FIG 9 Steady cruise load case Top-Wing trim incidence angles for given center-of-gravity locale.

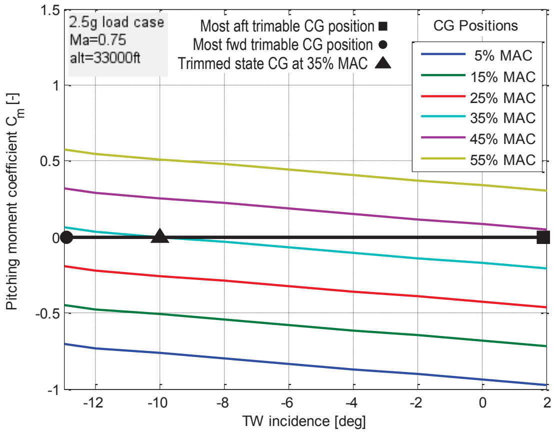

FIG 10 2.5g load case under cruise conditions Top-Wing trim incidence angles for given center-of-gravity locale.

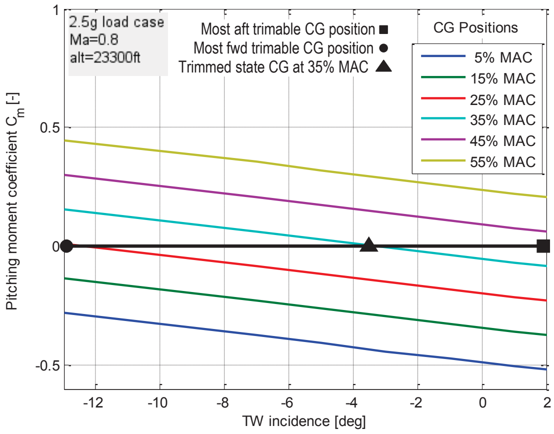

FIG 11 2.5g load case (flight envelope corner) Top-Wing trim incidence angles for given center-of-gravity locale.

FIG 10 (previous page) displays the result of the trim study for different TW incidence angles and CG positions for the 2.5g load case at flight level condition. The trimmable CG range is decreased compared to the 1.0g level cruise with a result of 33-44% MAC. At typical operational CG position of 35% MAC, the TW incidence angle for trim is 9.9° TEU.

The result of the trim study for the 2.5g load case at maximum dynamic pressure is displayed in FIG 11 (previous page). The trimmable CG position range is 24-39% MAC with 3.3° TEU for trim at typical operational CG position of 35% MAC. An implication of this outcome means the most aft CG allowable is approximately 14%MAC short of the maximum aft required with respect to loadability considerations [3].

The varied incidence angles of the TW result in different forms of deformation of the wingbox. FIG 2 shows the deformation of the CW for the 1.0g and the 2.5g load case for a trimmed state assuming typical cruise conditions contrasted against the wing original jig shape.

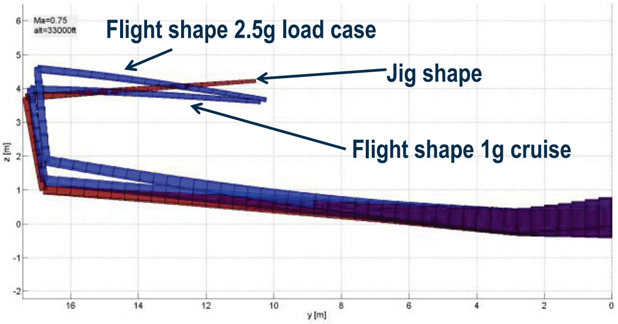

FIG 2 Deformations of C-Wing for typical cruise condition and worst case 2.5g symmetric pull-up maneuver.

6.2. Drag Estimation

The CW design aims at the reduction of the vortex-induced drag. The minimum vortex-induced drag for the examined CW layout was 152 dct and was achieved for 5.0° TED, see FIG 3. However, this is beyond the operational limit of the stabilator.

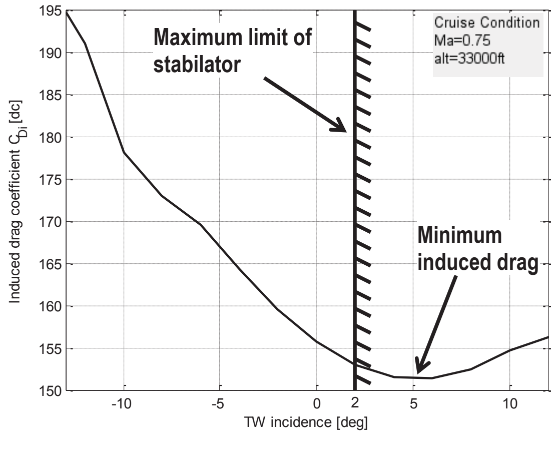

FIG 3 Vortex-induced drag of the C-Wing for different Top-Wing incidence angles.

For a trimmed state for a CG position of 35% MAC the TW incidence angle is 2.0° TEU, see FIG 9 in Section 6.1. FIG 4 displays the lift distribution for the trimmed state at 1.0g level flight condition. FIG 5 shows the lift distribution for a trimmed state for the 2.5g maximum dynamic pressure load case. It is notable that the tendency is for a more gentle trapezoidal lift distribution on the MW – mimicking a typical more triangular lift distribution for the primary lifting surface of aircraft configurations employing a wing plus stabilizer combination.

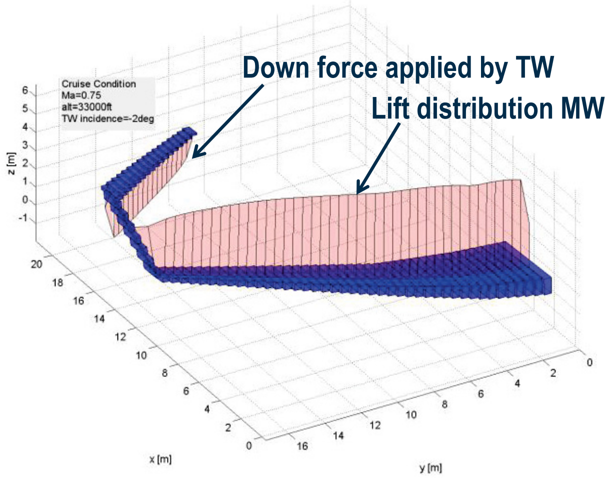

FIG 4 Lift distribution of C-Wing with down force at trimmed state at typical cruise conditions.

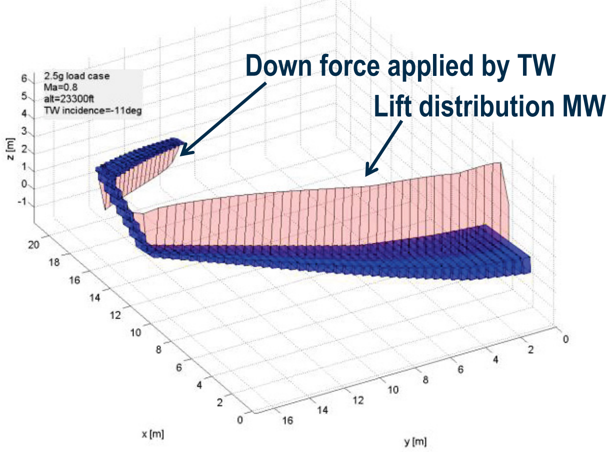

FIG 5 Lift distribution of C-Wing for 2.5g maximum dynamic pressure load case.

In TAB 5 overleaf the estimated drag values of the considered configurations are stated for a trimmed state of both configurations (CG at 35% MAC).The vortex-induced drag of the CW is 160 dct and the vortex-induced drag of the RW with stabilizer configuration 188 dct. The vortex-induced drag of the CW is 14.9% lower than for the conventional RW plus stabilizer configuration. Including the zero lift drag, the total drag of the CW is 9.1% lower than the RW configuration. The estimated zero lift drag used the component building up method [10] and was corrected for interference as well as three-dimensional effects. The 9.1% decrease in total drag means an increase in the aerodynamic efficiency. However, at aircraft level, considering the zero lift drag of the fuselage, fin, nacelles and pylons as well, the total drag of the CW versus the RW with stabilizer configuration is -6.8%.

TAB 5 Drag estimation of C-Wing and Reference Wing plus stabilizer configuration at trimmed state.

Property	Unit	Drag
CW vortex-induced drag	dct	160
CW zero lift drag	dct	89
Total drag of CW	dct	249
RW vortex-induced drag	dct	180

RW zero lift drag	dct	72
RW: Stabilizer vortex-induced drag	dct	8
RW: Stabilizer zero lift drag	dct	14
Total drag RW configuration (RW+stabilizer)	dct	274
Difference total vortex-induced drag CW to RW+stabilizer	%	-14.9
Difference total drag CW to RW+stabilizer	%	-9.1

6.3. Enhancing the Top-Wing Authority Through Adaptive Utilities

The function of the STW is to provide static stability in pitch, trim for not only high-speed but low-speed operations, thereby ensuring control authority for critical cases like take-off rotation, de-rotation during landing and full-thrust go-around maneuvers. 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 maneuver, take-off rotation, landing de-rotation and go-around were studied by Ref. [4]. 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 an idea to augment C-Wing functionalities, efficiency and authority for stability and control purposes using adaptive structures for the TW.

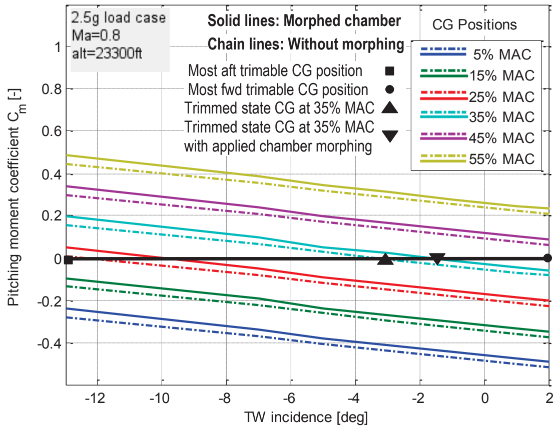

FIG 6 2.5g load case (flight envelope corner) Top-Wing trim incidence angles for given center-of-gravity locale.

Upon examination of the dof sensitivities [11] it was concluded that manipulation of camber and twist would best complement the stabilator-type functionality of the TW. Although trim and control authority for low-speed operations are not considered in this particular study, as a first step it was decided to investigate the feasibility of adopting a 5.0% camber in the context of aircraft states presented in this paper. FIG 6 shows the adoption of 5.0% camber (as opposed to the original approximately 1.0% camber of the Ce-Liner TW) for a symmetric 2.5g pull-up case at the flight envelope maximum dynamic pressure corner point (M0.80 at 23300 ft). It was observed that an adaptive camber feature could enable potential to expand the allowable CG range from 24-39% MAC to 21-41% MAC for stabilator incidence angle sweep of 13° TEU to 2.0° TED.

6.4. Mass Estimation

The mass predictions for the considered wings are stated in TAB 6. As the RW utilizes a stabilizer in order to manipulate pitching moment, for sake of conducting an equitable comparison the mass of the stabilizer is added to the mass of the RW. As the EIS for the Ce-Liner is 2035, the assumed material for the CW, and, the RW plus stabilizer combination, was assumed to be Carbon Fiber Reinforced Plastic (CFRP) with corresponding properties itemized in TAB 6.

TAB 6 CFRP material properties [12]

Material property	Unit	Value
Elastic Modulus	kN/mm²	69.0
Shear Modulus	kN/mm²	27.0
Density	kg/m³	1600
Yield Strength	N/mm²	550.0

Analyses have shown that a reasonable target weight reduction for the wingbox is around 32% compared to a wing system made from aluminum and this bodes well with previous studies presented in Ref. [13]. After the study was finalized, it was found the CW design is 3.9% heavier than the RW plus stabilizer combination. Although a weight penalty for the CW has been established, the authors consider this to be sufficiently modest when one appreciates the potential in aerodynamic efficiency improvement afforded by the CW.

TAB 7 Mass predictions for C-Wing and Reference Wing plus stabilizer combination (CFRP assumed).

Wing	Unit	Value
Estimated RW mass	kg	10060
Estimated stabilizer weight	kg	590
Total mass of MW + stablizer	kg	10650
Estimated CW mass	kg	11060
Difference CW to reference wing	%	+3.9

7. CONCLUSION AND OUTLOOK

With the results of the trim study for different angles of TW incidences it could be shown that it is possible to trim the Ce-Liner. For the 1.0g cruise condition the trimmable center of gravity (CG) position range is from 15 to 44% Mean Aerodynamic Chord (MAC) and a Top-Wing (TW) incidence angle of -2.0° is required to trim a CG position of 35%MAC. For the 2.5g load case at flight level condition the possible CG range, which can be trimmed, is decreased and reaches from 33 to 44%. In the 2.5g load case at maximum dynamic pressure the trimmable CG position range is 24 to 39% MAC. Very preliminary studies have shown that incorporation of variable camber (an additional 4.0% assumed on this occasion) for the TW would allow, from a perspective of trimmability, approximately 3%MAC more forward and 2%MAC more aft CG, thus increasing scope for loadability of the aircraft.The vortex-induced drag of the C-Wing (CW) was calculated to be 14.9% less than the one for the Reference Wing (RW) with stabilizer for a trimmed state for a CG position of 35% MAC. The total drag reduction of the CW compared to the reference configuration was 9.1% at a trimmed state for a CG position of 35%MAC at flight level condition. Similarly, this produced an aircraft-level drag reduction of 6.8%. Therefore, the CW offers the possibility to increase the aerodynamic efficiency and to contribute to lower energy consumption of the aircraft.The estimated weight of the CW was 3.9% heavier than the estimated weight of the RW with stabilizer. Therefore, the CW has a slight weight penalty compared to the considered conventional configuration.

Since it is not possible to trim the Ce-Liner in the entire CG range and different load cases by only changing the incidence angle of the TW additional degrees-of-freedom have to be added. To keep the morphology of the wing relatively simple a variable camber of the TW airfoil, as described in this paper, in combination with a variable sweep of the TW could be a solution. With a larger camber the angle of attack of the TW can be increased and a greater down force is produced. The variable sweep of the TW increases the lever arm of the TW with respect to the CG position. Hence, the influence of the TW on the pitching moment is also increased and with less down force a larger pitching moment is produced. Another possibility is to equip the pylons with additional control surfaces. The engines of the Ce-Liner are mounted at the rear fuselage. The pylons have a small surface, but a large lever with respect to the CG position of the aircraft. Hence, the use of the pylons could improve the trimmable CG range. Also shifting the minimum vortex-induced drag towards a trimmed state of the Ce-Liner for cruise condition and at least one relevant CG position such as 35%MAC could be reached with a redesigned TW. Such a layout could further decrease the vortex-induced drag during cruise. Optimizing the position of the wing itself with respect to the fuselage is also a possibility to influence the trimmable CG position range. By moving the entire wing aft a better match between trim authority and loadability for aft CG locales can be reached with the same TW incidence angle range given this study.

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