Investigation and design of a C-Wing passenger aircraft

Karan BIKKANNAVAR*[,1], Dieter SCHOLZ[2]

*Corresponding author
*[,1]Wichita State University, Wichita, KS 67260, USA
karanbikkannavar@gmail.com
[2]Aircraft Design and Systems Group, Hamburg University of Applied Sciences,
Berliner Tor 9, 20099 Hamburg, Germany
info@profscholz.de

DOI: 10.13111/2066-8201.2016.8.2.3

Received: 11 May 2016 / Accepted: 25 May 2016

Abstract: *A novel nonplanar wing concept called C-Wing is studied and implemented on a commercial aircraft to reduce induced drag which has a significant effect on fuel consumption. A preliminary sizing method which employs an optimization algorithm is utilized. The Airbus A320 aircraft is used as a reference aircraft to evaluate design parameters and to investigate the C-Wing design potential beyond current wing tip designs. An increase in aspect ratio due to wing area reduction at 36m span results in a reduction of required fuel mass by 16%. Also take-off mass savings were obtained for the aircraft with C-Wing configuration. The effect of a variations of height to span ratio (h/b) of C-Wings on induced drag factor k, is formulated from a vortex lattice method and literature based equations. Finally the DOC costing methods used by the Association of European Airlines (AEA) was applied to the existing A320 aircraft and to the C-Wing configuration obtaining a reduction of 6% in Direct Operating Costs (DOC) for the novel concept resulted. From overall outcomes, the C-Wing concept suggests interesting aerodynamic efficiency and stability benefits.*

Key Words*: C-Wing, aspect ratio, induced drag factor, vortex lattice method, Oswald factor.*

1. INTRODUCTION

Recent advancements in technologies have embarked aircraft designers to propose futuristic designs of transport aircraft which were once discredited. Smaller improvements in aircraft configuration as a whole have proved promising and efficient. Many theories have been put forward in the last two decades on nonplanar wing configurations such as box-wings, ring-wings, joined wings, and wing with winglets, aiming at their potential in reducing vortex drag (or induced drag). Each configuration has differences related to geometry, stability and trim. The only configuration that has been considered so far by the commercial aviation sector are wings with winglets. Developments of other nonplanar configurations on commercial aircraft have been presented recently to showcase the general feasibility and the possibility of further fuel and cost savings due to drag reduction. The present paper discusses one of such nonplanar wing concept, namely, the “C-Wing” design. The reason for adopting this design concept is mainly due to their potential for lower vortex drag at a fixed span, a key constraint for large commercial transport aircraft as described by McMaster *et al*. [1, 2]**.** Naturally, increasing the wing span may easily reduce induced drag. However this method might not be adopted primarily due to airport terminal parking constraints, and structural weight and hence costs. Therefore different configurations should be assessed in order to overcome such constraints.

2. OVERVIEW OF NONPLANAR WING CONFIGURATION

A nonplanar wing configuration is one in which the aircraft wing is seen in two-dimensional plane unlike a planar wing which is seen as a straight wing in one plane. Nonplanar wings are divided based on geometric characteristics which include biplanes, triplanes, c-wings, box wings, joined wings and ring wings. Nonplanar wing tips comprise wings with endplates, winglets, split tips, crescent tips. These nonplanar wings have the advantages of reducing drag compared to planar wings without extending the wing span. Drag reduction is achieved for nonplanar shapes due to an increased span efficiency. Geometrically, the wing span is permitted to have vertical extension of certain lengths. Figure 1 shows the span efficiencies of various nonplanar geometry shapes with height to span ratio of 0.2.

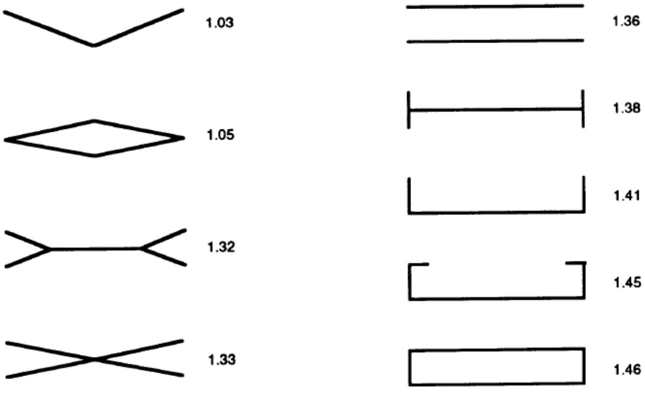

Figure 1. Span efficiency of various nonplanar shapes with *h/b* ratio of 0.2 (Kroo 2005)[2]

Such nonplanar wing concepts are promising because of the possibility of improved high lift performance, effective structural efficiency, or desirable stability and control characteristics [2]. Likewise, the C-Wing concept achieves nearly the maximum induced drag reduction as associated with box wing concept, but also rules out the additional area required closing the box wing. This offers additional profile drag savings.

The C-Wing geometry shape was discovered by the application of a variable complexity algorithm with an objective to find a wing shape of fixed lift, span, and height with minimum drag. The system discovered winglets and then added a horizontal extension to the winglet forming a C-like shape [4]. The first application of this C-Wing concept to an aircraft design arose due to span constraints associated with large civil transport airport compatibility. Kroo [5] discusses different concepts for prediction and reduction of induced drag. Large civil transport aircrafts with conventional configuration have issues related to span limit, location of outboard engine, wake vortices, runway limits, structural limits, and wake vortices. Using the C-Wing configuration, the span of a conventional aircraft can be reduced. Also the C-wing horizontal surfaces provide positive trimming moments when optimally loaded and simultaneously increase stability in pitch and yaw for a given area as they are less affected by wing downwash. This intimates for the removal of horizontal tail and employment of aft-fuselage-mounted engines [1]. This particular design can incorporate very thick airfoils and the possibility of including a part of the passenger cabin partly inside the wings. Adopting this advantage, Blended Wing Body (BWB) designs have been proposed. More effective use of high lift devices can be enabled due to shift in aerodynamic center and efficient trim without any large sweep angle. This reduced sweep offers further opportunities in reducing drag utilizing a laminar flow concept [2]. Any structural engineer would question flutter penalties linked with torsion and coupling. However, the swept C-Wing concept is expected to lower the torsional frequencies of the system and allow coupling between bending and torsion modes. By exploiting multi-surface approach, one may independently control lift/torsion in order to overcome aileron reversal effects as shown in Figure 2. This multi surface also increases significant control of flutter modes.

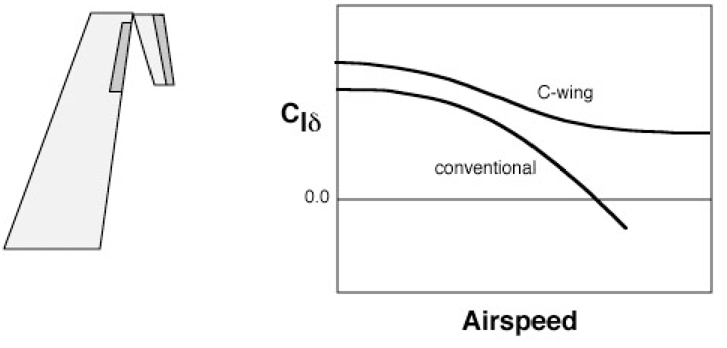

Figure 2. Multi-Surface approach [2]

In accordance, Bauhaus Luftfahrt [6] has proposed and developing a nonplanar C-Wing three-surface configuration designed for a tailless universally electric passenger aircraft. This aircraft utilizes a novel Self-Trimming Wing (STW), with inherent poly-morphing systems to ensure stability and control characteristics. The nonplanar C-Wing assembly utilizing three elements or surfaces is shown in Figure 3.

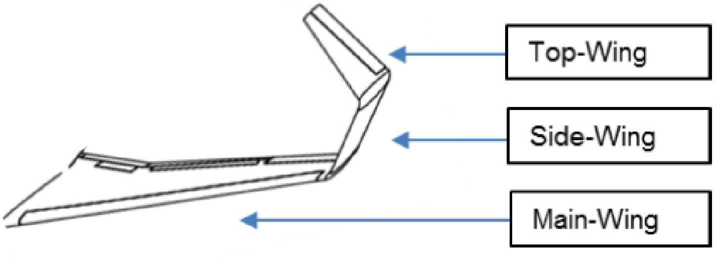

Figure 3. Non-planar C-Wing layout, Bauhaus Luftfahrt [6]

The study demonstrates reduction of vortex-induced drag coefficient ($C_{D,i}$) via two mechanisms. The first mechanism is the change of load distribution on the main wing. In the second mechanism, a "thrusting effect" is attributed to the top wing where its position is influenced by main wing downwash. This produces a downward force that causes a forward-oriented induced drag, which is nothing but "thrusting effect". The wing behavior and performance results demonstrate considerate reduction in vortex induced drag during cruise compared to planar wing with similar surface area. The analysis of novel adaptive C-Wing also show effective capability of self-trimming the aircraft for different phases of mission profiles without the necessity of additional aft or canard like horizontal surfaces.

In the current paper, the aim was not to emphasize on performance of the C-Wing concept alone, but rather to provide feasible, promising, and alternative solution to existing conventional aircraft design with current technologies and resources.

3. C-WING AERODYNAMICS

From the fundamentals of aerodynamics, it can be said that due to the pressure difference on a finite wing surface air tends to flow from the lower wing surface to the upper wing surface causing a change in the speed and direction of spanwise and chordwise flow, eventually twisting the flow and producing vortices along the wing trailing edge. These resulting wing tip vortices deflect the airflow downwards and thus inducing downwash in the vicinity of the wing. This induced downwash accounts for the induced drag. Various wing tip devices have been proposed and implemented; each having their pros and cons. The most widely adopted wing tip design is the wing with winglets. This vertical extension of the wingspan reduces the wing tip vortices and hence downwash, ultimately minimizing induced drag. Now introducing the concept of the “C-Wing” for aircraft configuration has been intriguing in terms of its aerodynamic characteristics. Upon addition of a horizontal wing extension to vertical surface thus forming a “C-Wing”; the high pressure on the upper horizontal wing extension causes a downward producing force. This downforce however isn’t much beneficial as it affects the lift distribution of the lower main wing. This effect can be seen in Figure 5 with span efficiency values of 1.45 and 1.46 depicting “C-Wing” characteristic. To counteract this effect, the upper horizontal wing can be swept backwards as shown in Figure 4, to improve the flow behavior and also stability characteristics.

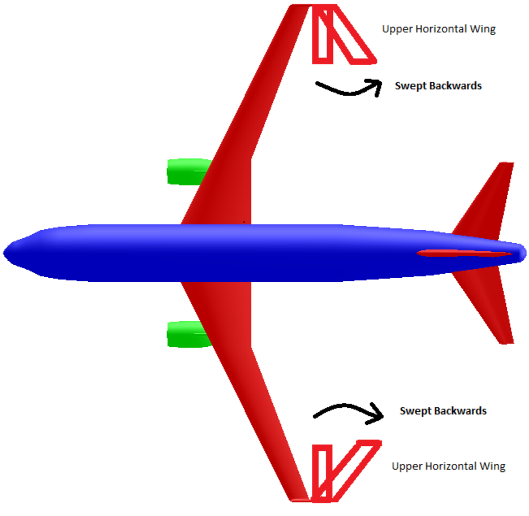

Figure 4. Top view of the C-Wing aircraft with a notion to improvise lift characteristics

Figure 5 demonstrates the optimal lift distribution of different geometries starting with planar wing to box wing. The winglet is loaded inwards due to the circulation carried by the main wing onto the winglet. When a horizontal surface is added to the winglet, forming the “C-shape”, the circulation is further extended from the winglet, producing a download force on this surface for minimum induced drag at fixed total lift. Likewise, this download on the C-Wing horizontal extent has shown favorable affects in terms of structural weight, stability and trimming. When the upper surface is further extended forming a box wing, it is then seen that the upper wing efficiently carries an upload. The reason is, with closed systems we can superimpose a vortex loop with constant circulation. Though the local loading changes, the wake (hence the lift and vortex drag) remains unchanged because the circulation is constant [5]. This is the reason why the C-Wing shape approximates so closely to box wing. Hence we can eliminate the inner part of the upper wing by simply adjusting the constant circulation which eventually minimizes additional friction drag and weight.

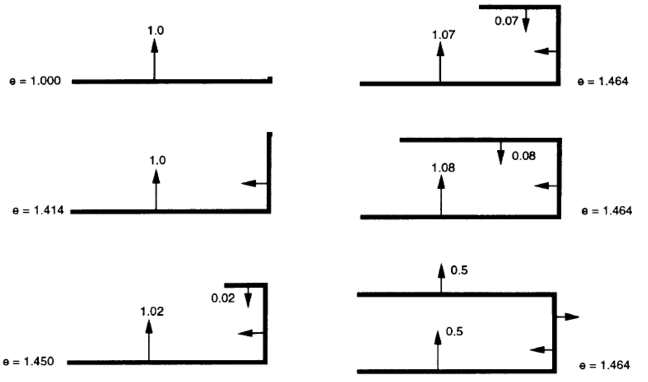

Figure 5. Load distribution of different geometries [1]

One other potential advantages of C-Wing geometry is the development of the trailing vortex wake system. Figure 6 depicts the wake structure comparison for a planar and a C-Wing configuration obtained with wind tunnel data at Tuskegee University. The C-Wing tends to distribute the vortices in the wake over a longer distance downstream, reducing the intensity of the wake. Also since the vortices shed from the tip extensions of the upper wing and wing tips are close together, the breakdown of wake system accelerates. This illustrates primary difference between the wake of the conventional design and the C-Wing design.

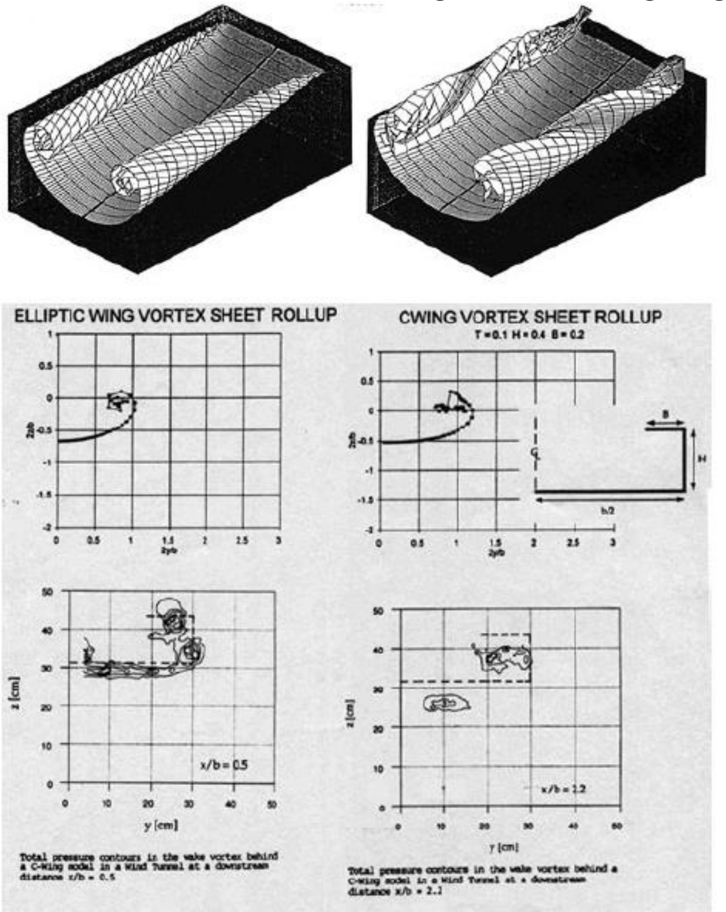

Figure 6. Wake structure comparison for a planar and C-Wing Configuration [1]

On the contrary, Verstraten [7] presents results of the performance of several planar and nonplanar wing configurations using numerical method. The paper states that C-wings perform marginally better than wingletted wings (same root bending moment) for vertical winglet heights up to 25% of the semispan and there is no C-Wing that performs better for vertical height of 28% of the semispan. Therefore, questioning any real aerodynamic advantage to the use of C-Wings.

4. AIRCRAFT PRELIMINARY SIZING METHOD

Preliminary sizing is one of the sequences of activities performed during the initial stages of the aircraft design. In this paper, a preliminary sizing method [3] has been adopted.
The latter is also possible without detailed knowledge of the geometry of the aircraft. The aircraft is more or less reduced to a point mass. Starting with preliminary sizing phase, certain requirements have to be defined and evaluated initially. Some of them are payload, range, Mach number, take off field length, landing field length, climb gradient during second segment. Secondly, an aircraft configuration and a propulsion system are chosen and trade-off studies are performed before executing the preliminary sizing method. During the sizing method execution, few assumptions like maximum lift coefficient (during take-off and landing), maximum glide ratio (during take-off, cruise and landing) will need to be made.

Eventually, a two-dimensional optimization algorithm is performed in the form of a matching chart considering different flight phases together with their related aircraft performance: take-off, 2nd segment climb, cruise, landing and missed approach. The two preferred optimization variables assured are low thrust-to-weight ratio and suitable (high) wing loading. Using all these optimized values the design parameters calculated are: take-off mass, fuel mass, operating empty mass, wing area, take off thrust.

The following paragraphs briefly explain the sizing phases.
Landing distance provides a maximum value for the wing loading m / S (reference value: m_{MTO} / S_W). The Wing loading at maximum landing mass is

$$\frac{m_{ML}}{S_W} = \frac{\rho \cdot V_{S,L}^2}{2 \cdot g} \cdot C_{L,max,L} \tag{1}$$

The maximum lift coefficients $C_{L,max}$ are obtained from empirical data. Similarly the ratio of maximum landing mass m_{ML} to maximum take-off mass m_{MTO} is given as

$$\frac{m_{MTO}}{S_W} = \frac{m_{ML}/S_w}{m_{ML}/m_{MTO}} \tag{2}$$

'Take-Off distance' provides a minimum value for the thrust-to-weight ratio as a function of the wing loading: $T / (m \cdot g) = f(m / S)$ with reference value: $T_{TO} / (m_{MTO} \cdot g)$.

$$\frac{T_{TO}/m_{MTO} \cdot g}{m_{MTO}/S_w} = k_{TO}/s_{TOFL} \cdot \sigma \cdot C_{L,max,TO} \tag{3}$$

with k_{TO} = 2.34 m^3/kg. The ratio from thrust-to-weight ratio and wing loading pursuant to above equation must not undershoot if the aircraft is to meet requirements. "Climb rate in the second segment" and the "climb rate during the missed approach" provide minimum values for the thrust-to-weight ratios $T / (m\ g)$. If the climb is also to be possible with a failed engine, the thrust-to-weight ratio relative to the thrust of all the engines must to correspondingly greater. For a number of engines n_E, at least a thrust-to-weight ratio of

$$\frac{T_{TO}}{m_{MTO} \cdot g} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E} + sin\gamma\right) \tag{4}$$

must be stipulated. Where $E=L / D$ and $sin\gamma \approx \frac{climb\ gradient}{100}$.

"Cruise" represents the cruise analysis that provides a minimum value for the thrust to weight ratio as a function of the wing loading: $T / (m \cdot g) = f\ (m / S)$. A stationary straight flight at cruise altitude is assumed for which two equations can be used, lift equals weight and drag equals thrust. From these two equations, the parameters wing loading and thrust-to-weight ratio are calculated.

- Wing loading is given as a function of the parameters: lift coefficient C_L, Mach number M and altitude h).

$$\frac{m_{MTO}}{S_W} = \frac{C_L \cdot M^2}{g} \cdot \frac{\gamma}{2} \cdot p(h) \tag{5}$$

Where γ the ratio of specific heats and $p\ (h)$ is the pressure determined from the standard atmosphere.

- In cruise flight,

$$T_{CR} = D_{CR} = \frac{m_{MTO} \cdot g}{E} \tag{6}$$

Dividing the above equation by take-off thrust T_{TO} and rearranging,

$$\frac{T_{TO}}{m_{MTO} \cdot g} = \frac{1}{\left(\frac{T_{CR}}{T_{TO}}\right) \cdot E} \tag{7}$$

The above output values from the equations provide a set of relationships between the thrust-to-weight ratio and the wing loading. For all calculations it was ensured that wing loading and thrust-to-weight ratio always refer to take-off with MTOW, which made it possible to compare the values of different flight phases. From the above input values, mass estimation can be performed. The maximum take-off mass m_{MTO} is comprised of payload, fuel mass and the operating empty mass:

$$m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}} \tag{8}$$

The sizing procedure determines the relative operating empty mass from statistical analysis. It's observed that the relative operating empty mass increases with increasing thrust-to-weight ratio. The relative operating empty mass can be summarized as

$$\frac{m_{OE}}{m_{MTO}} = 0.23 + 1.04 \cdot \frac{T_{TO}}{m_{MTO} \cdot g} \tag{9}$$

The entire fuel mass consumed on the flight is calculated from the mission fuel fraction M_{ff} which includes flight phases from starting the engines to taxiing off after landing. These segments can be obtained from calculation or from statistics.

In the current paper, the Airbus A320 has been adopted as a reference aircraft. The objective is to perform preliminary sizing of A320 aircraft configuration with C-Wing concept. To achieve accurate values, the preliminary sizing method (tool) has to be validated for its results. Since the current A320 requirements and design parameters are already available in the database, preliminary sizing sequence will be performed and validated in order to check how accurate the sizing method/tool is. Lesser the difference between calculated and available results, more the accuracy of the sizing method/tool is!

Accordingly, the sizing sequence is repeated for C-Wing configuration and validated with the reference aircraft (values obtained from sizing method). The optimum results (higher percentage difference) would denote the significance of the C-Wing concept. Table 1 presents the percentage difference of primary sizing parameters between available A320 data (CERAS, RWTH Aachen) [8] and sizing data calculated using the preliminary sizing method. As stated earlier, lesser the difference, more accurately the sizing method calculations have been carried out.

It can be seen that major parameters have an error difference of 2% or less, which means the calculations are marginally close to available A320 data. The aspect ratio was equally sized for the A320 wing span of 34m and hence the error difference of zero percentile. However, take-off thrust parameter obtained by sizing method was lower than available data since certain engine characteristics were not available.

This initial estimation was competent and promising to resume C-Wing sizing calculation using the preliminary sizing method.

Table 1 - Comparison of sizing parameters of A320 available data and preliminary sizing method calculations

Parameters	**A320 Available Data**	**Preliminary Sizing Method (Reference Aircraft)**	**Difference %**
Max. Take-Off mass (kg)	77000	75479	-2.0%
Max. landing mass (kg)	64500	65289	1.2%
Operating empty mass (kg)	42092	41261	-2.0%
Wing Area (m^2)	122.4	124	1.3%
Aspect Ratio	9.48	9.48	0.0%
Take-Off thrust of one engine (N)	117900	112743	-4.4%

The parameters obtained using the sizing method is now defined to as the reference aircraft. Now the preliminary sizing estimation for a concept aircraft with C-Wing configuration was also performed using the sizing method (hence the comparison) and validated against the reference aircraft.

Table 2 presents the percentile difference of the sizing parameters between reference aircraft and the C-Wing aircraft.

Considerable mass savings are achieved. The maximum take-off mass and operating empty mass of the A320 with C-Wing configuration is lower by almost 7% respectively compared to reference aircraft previously calculated. The maximum landing mass difference is about 5%.

About 10% reduction in wing area is achieved in the C-Wing concept aircraft mainly due to higher wing loading and low landing mass.

Also from the previously calculated wing span of 34m, the constraint was extended to agreeable 36m span for the C-Wing configuration. Together with the reduced wing area the aspect ratio increased and hence increasing the Oswald factor. So a large reduction by almost 16% in fuel mass was achieved.

Table 2 - Comparison of sizing parameters of reference A320 with C-Wing aircraft using sizing method

Parameters	**Reference Aircraft - A320**	**Concept Aircraft A320 with C-Wing**	**Difference %**
Max. Take-Off mass (kg)	75479	70507	-6.6%
Max. landing mass (kg)	65289	61905	-5.2%
Operating empty mass (kg)	41261	38542	-6.6%
Fuel mass (kg)	14218	11964	-15.9%
Wing Area (m^2)	124	112	-9.7%
Aspect Ratio	9.48	11.6	22.4%
Take-Off thrust of one engine (N)	112743	88865	-21.2%

Figure 7 and 8 show three view drawings of the Airbus A320 with C-Wing configuration to give a perspective about the concept. OpenVSP software was used to design the full-scale aircraft model.

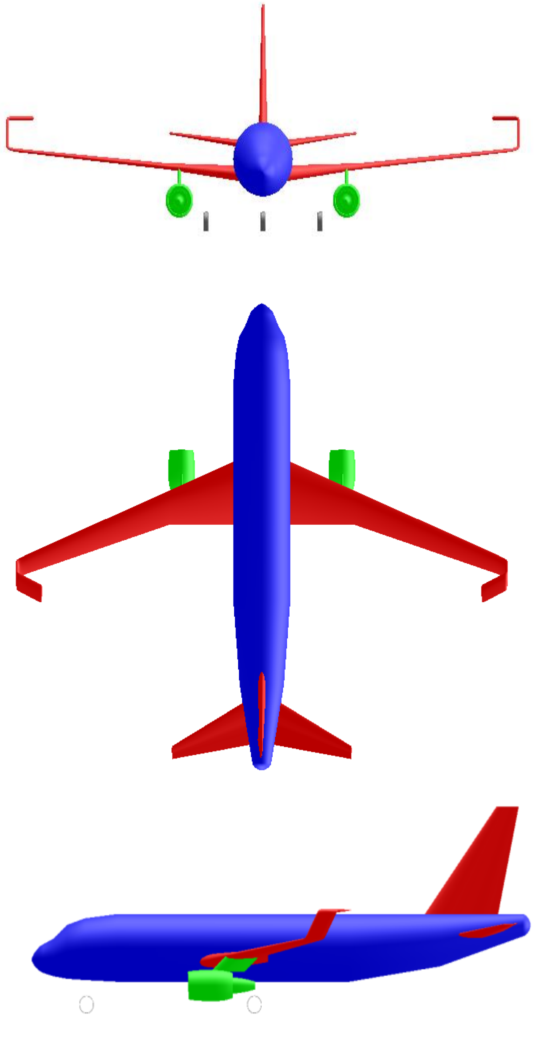

Figure 7. Three view Drawing of A320 aircraft with C-Wing concept (*h/b*=0.1)

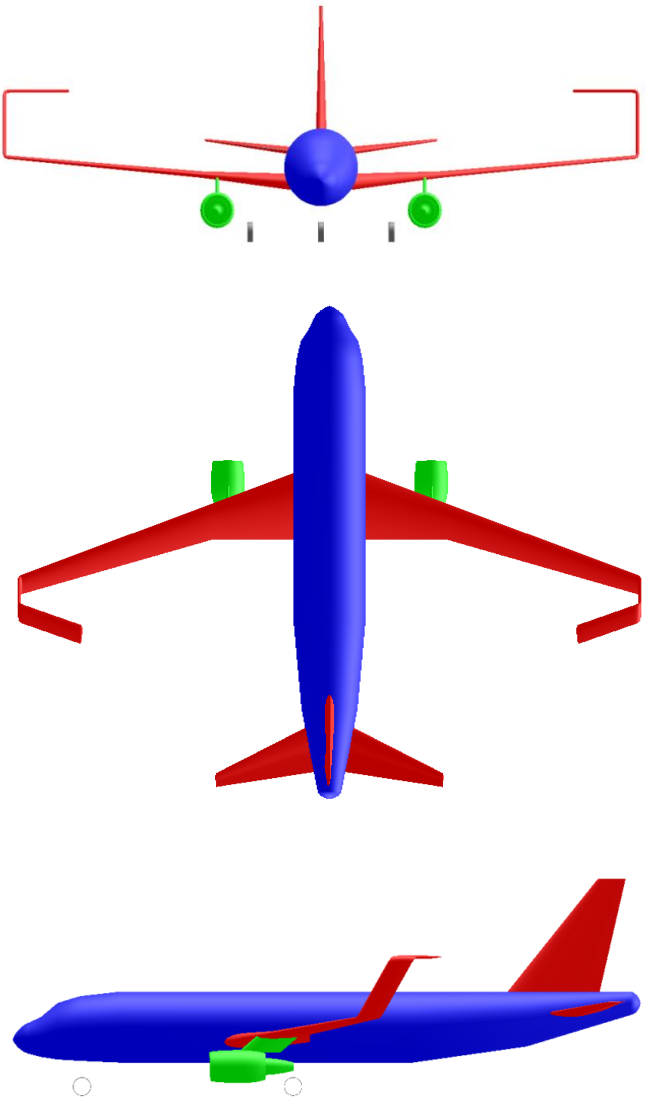

Figure 8. Three View Drawing of A320 aircraft with C-Wing concept (*h/b*=0.2)

5. INTRODUCTION TO VORTEX LATTICE METHOD

To determine the minimum induced drag of the configuration, a discrete vortex method developed at Virginia Tech has been utilized. In this method, the aerodynamic surfaces are represented by a set of discrete horseshoe vortices. The induced drag calculations are performed in the trefftz plane as a function of the velocity induced by the trailing segments of the horseshoe vortices [9]. To execute the code, geometrical and design conditions are entered in the text file. The plots of the aircraft configuration can be viewed in Matlab workspace for which the codes are available. The calculation have been made using 400 vortices considering the accuracy [10].

In the current paper, as stated earlier the reference Airbus A320 wing parameters are used. The C-Wing geometry configuration with *h/b* ratios 0.1, 0.2, 0.3 and 0.4 have been calculated respectively and are plotted in Matlab. Geometry plots of *h/b* ratios 0.1 and 0.2 are shown in Figure 9.

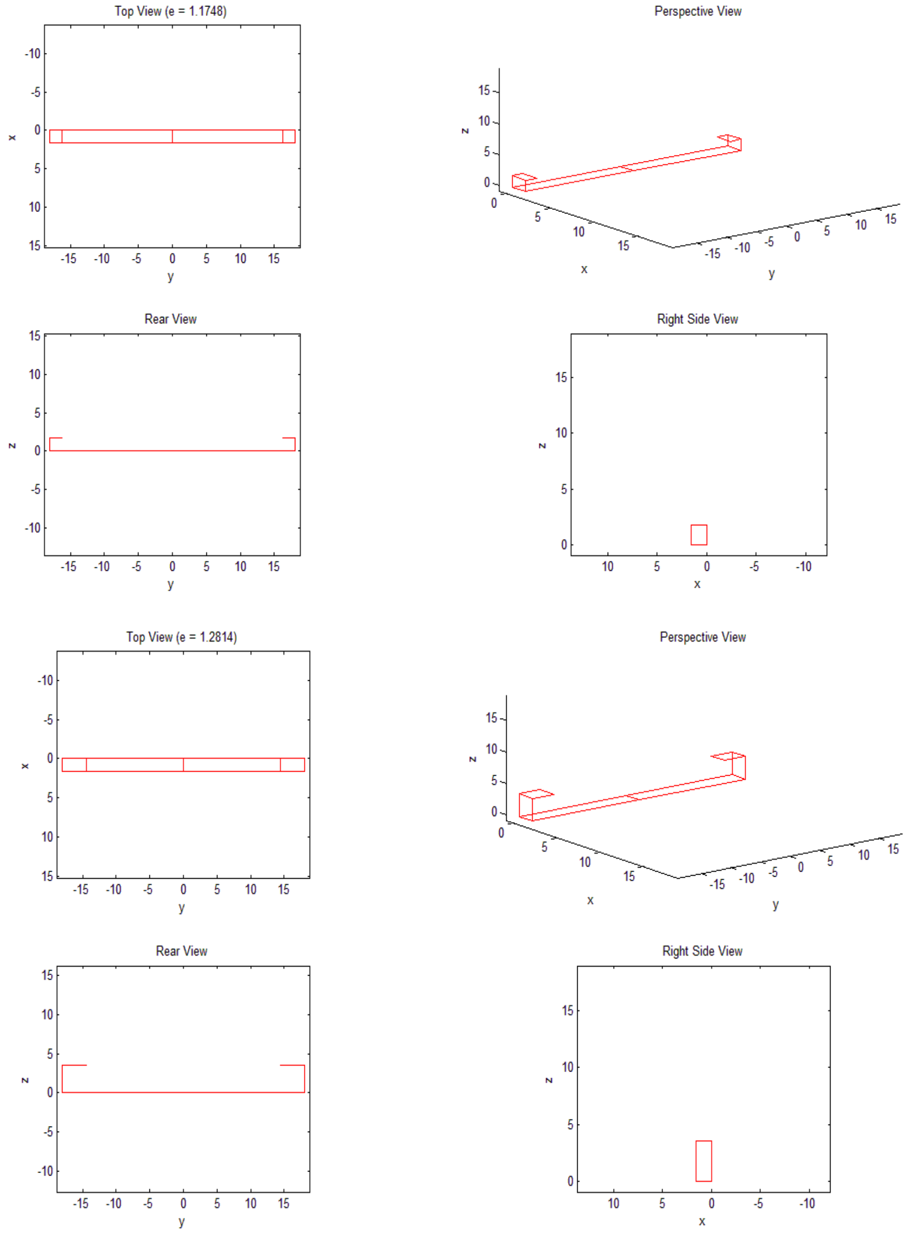

Figure 9. Geometry plot for C-Wing configuration, *h/b* ratio of 0.1 (top) and 0.2 (bottom) respectively

The *k* values obtained in Table 3 are plotted in Figure 10 representing idrag values for new wing of span 36m with C-Wing configuration (varying *h/b*). Similar calculations were also performed and plotted representing idrag values for existing or current wing span of 34m and varying *h/b* ratios (C-Wing).

Table 3-idrag calculations for C-Wing

h/b	$C_{D,i}$	e	k=1/e
0.0	0.0123	1.0004	0.99952
0.1	0.0103	1.1961	0.83600
0.2	0.0094	1.3064	0.76546
0.3	0.0088	1.4017	0.71337
0.4	0.0082	1.4906	0.67083

6. ESTIMATING THE OSWALD FACTOR FOR NONPLANAR CONFIGURATIONS

The airplane drag can be written in dimensionless form as,

$$C_D = C_{D,0} + C_{D,i} = C_{D,0} + \frac{C_L^2}{\pi A e} \tag{10}$$

where $C_{D,0}$ is the zero-lift drag or viscous drag and $C_{D,i}$ is the drag due to lift or lift-induced drag. The factor e, also called Oswald efficiency factor, accounts for nonoptimal loading and lift-dependent viscous drag. The above equation can be rewritten in dimensional form as

$$D = qSC_{D,0} + \frac{L^2}{q\pi b^2 e} \tag{11}$$

This dimensional form reveals that induced drag depends on the wing lift, speed, and span and not on the aspect ratio, a fact that is underappreciated since the nondimensional form is so well-known [5]. These above equations signify by which one might derive the drag due to lift efficiency of a given design. One can determine the values of the constants $C_{D,0}$ and e, by fitting C_D versus C_L^2 and considering the slope. Nita [11], present estimation of Oswald factor (also called as span efficiency factor) from basic aircraft geometrical parameters. Oswald factor e for nonplanar configurations is given as

$$e_{NP} = e \cdot K_{e,NP}$$

$$e_{NP} = e_{theo} \cdot k_{e,f} \cdot k_{e,Do} \cdot k_{e,M} \cdot k_{e,NP}$$

$$e_{NP} = \frac{k_{e,M}}{Q + P\pi A} \cdot k_{e,NP}$$

The terms Q and P cover the inviscid (vortex drag) and viscous part of the induced drag coefficient respectively. Whereas e_{theo} is theoretical Oswald factor: inviscid drag due to lift only, and $k_{e,f}, k_{e,Do}, k_{e,M}, k_{e,NP}$ are the correction factors for losses due to the fuselage, viscous drag due to lift and compressibility effects on induced drag, respectively.

The following general relations can be written via a factor called k_{NP},

$$e_{NP} = \left(1 + \frac{2}{k_{NP}}\frac{h}{b}\right)^2 \cdot e = k_{e,NP} \cdot e \tag{12}$$

The values of $k_{e,NP}$ can be obtained from Kroo‘s calculations and the factor k_{NP} can then be estimated.

The Box Wing Equation Applied to the C-Wing

The intention here is to find an equation obtained from literature originally for a box wing to calculate better k values compared to idrag results. The symbol k is refered to as the induced drag factor. It is defined as the ratio between the induced drag of the C-Wing and the induced drag of the reference wing.

$$k = \frac{D_{I,C-Wing}}{D_{I,ref}}$$

The span efficiency factor e and k are related as

$$e = \frac{1}{k}$$

The general form of the equation obtained from the literature [11] is defined as

$$\frac{D_{I,C-Wing}}{D_{I,ref}} = \frac{e_{ref}}{e_{C-Wing}} = k = \frac{k_1 + k_2 \cdot h/b}{k_3 + k_4 \cdot h/b} \tag{13}$$

k_1/k_3 is the value for $h/b = 0$.
The value of $k_1/k_3 = 1$. k_2/k_4 is the limit value for high h/b ratios. A possible limiting value of 0.5 could be forced on the equation for two wings, (main wing and top wing) at a large distance. The k-parameters are calculated using curve fitting algorithm with minimal errors.

For h/b ratios of 0 to 0.4, k values from idrag are obtained and similarly k values from the equation are obtained respectively. The error on each point is calculated as the difference between the idrag value and the value obtained from the equation. Curve fitting was performed with the Excel solver minimizing the sum of errors squared on the idrag points. This yielded a set of k-parameters with small errors satisfying the condition k_1/k_3=1. The limit value k_2/k_4 for high h/b ratios was calculated to be 0.498. The procedure was carried out for the current wing span of 34m and the new wing span of 36m respectively. Differences between the two can be neglected.

$$\frac{D_{I,C-Wing}}{D_{I,ref}} = k = \frac{0.52 + 1.21 \cdot h/b}{0.52 + 2.43 \cdot h/b}$$

or,

$$e = \frac{1}{k} = \frac{D_{I,ref}}{D_{I,C-Wing}} = \frac{0.52 + 2.43 \cdot h/b}{0.52 + 1.21 \cdot h/b} \tag{14}$$

The values obtained from Equation 14 was plotted in the Figure 10 in comparison with idrag values previously obtained.

The Winglet Equation Applied to the C-Wing

A similar curve fitting approach was undertaken on the equation originally derived for winglets. Equation 15 below was used to calculate the induced drag factor and was compared with C-Wing data. The comparison was made as shown in Figure 10 to observe any significant difference between the two non-planar configurations.

$$e_{WL} = \left(1 + \frac{2}{k_{WL}} \frac{h}{b}\right)^2 \cdot e = k_{e,WL} \cdot e \tag{15}$$

Figure 10 also shows values obtained by Waeterschoot on a box-wing concept using the equation.

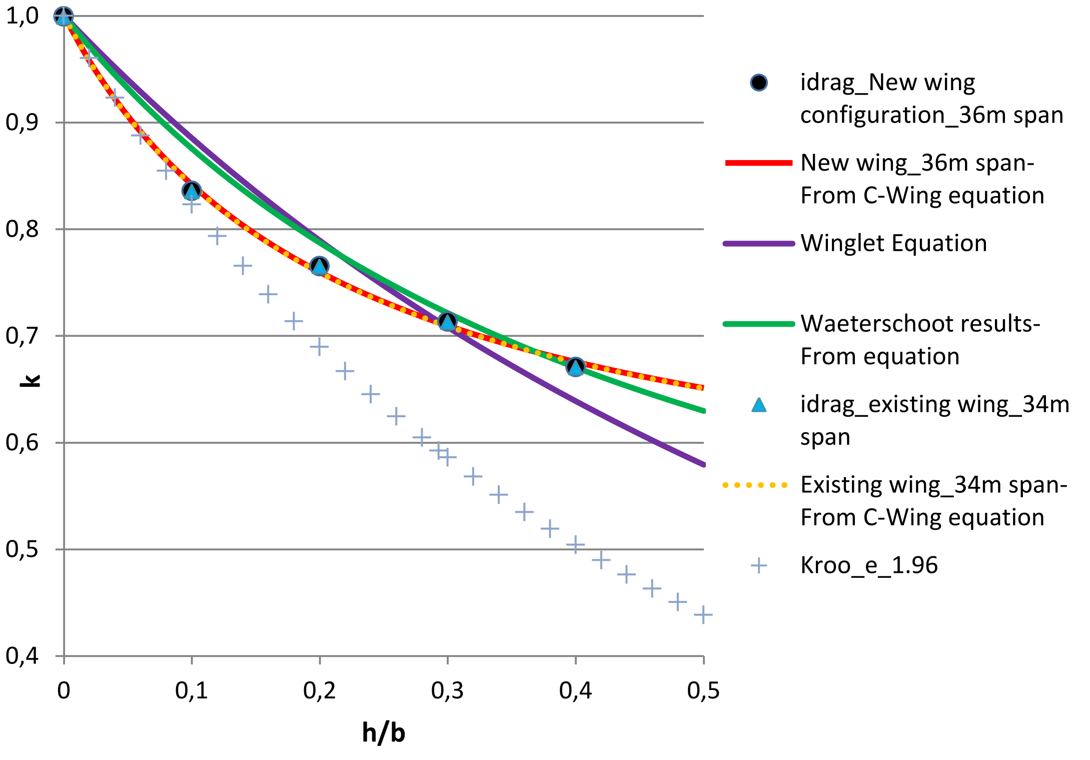

Figure 10. Comparison of induced drag factor k for C-Wing with varying h/b ratios

Lastly, value for the span efficiency factor of 1.45 stated by Kroo for *h/b* ratio of 0.2 was inputed into the general equation and a corresponding k_{NP} value of 1.96 was obtained. The equation was used to calculated *k* values for varying *h/b* ratios. These results are also plotted in Figure 10 for comparison.

Based on Figure 10, it is recommended to use Equation 14 to calculate the Oswald efficiency factor e for C-Wings.

7. COSTING METHODS

In the aviation world, an aircraft design is assessed based on cost analysis from the perspective of the aircraft manufacturer. The aircraft operator also evaluates and selects the aircraft depending on operating costs of the proposed design.

The aircraft manufacturer differentiates costing analysis between fixed costs and variable costs. Fixed costs or non-recurring costs are the costs incurred particularly during the project definition, testing and development phase. Variable costs (or recurring costs) are costs incurred by manufacturing and product support.

From the perspective of the operator, a whole series of models for cost analysis are used as described by Scholz [3] such as Life cycle costs (LCC), Cost of ownership (COO), Direct operating costs (DOC), Indirect operating costs (IOC), Cash operating costs (COC), Total operating costs (TOC).

This report discusses only DOC method used by the Association of European Airlines (AEA). To brief, Direct Operating Costs (DOC) include entire operating costs of the aircraft which sums up costs incurred due to depreciation, interest, insurance, fuel, crew, maintenance, fees and charges. COC are DOC without depreciation. Direct operating costs (DOC) was calculated as the costs incurred by an aircraft (a/c) for one year ($C_{a/c,t}$) for a specific aircraft trip characterized by a specific range R, a specific flight time t_f. It is also possible to relate the DOC to the distance flown and can be defined as aircraft mile costs $C_{a\backslash c,m}$. Here $n_{t,a}$ is the number of flights per year that an aircraft makes.

$$C_{a/c,m} = \frac{C_{a/c,t}}{R} = \frac{C_{a/c,a}}{n_{t,a}\, R} \tag{16}$$

The DOC can be further recorded by taking into account the payload of passengers and luggage. This is calculated as *seat-ton-mile* costs or *cargo-ton-mile* costs, for cargo plane.

$$C_{equiv,t,m} = \frac{C_{a/c,t}}{\left(m_{pax} + m_{baggage} + k_{cargo,CMD} m_{cargo,CMD} + k_{cargo,CLD} m_{cargo,CLD} + k_{cargo,B} m_{cargo,B}\right) R} \tag{17}$$

This equivalent ton-mile cost estimation was carried out for the current existing A320 aircraft and the aircraft with C-Wing configuration in terms of Euros and US dollars and the corresponding difference was noted. Table 4 presents DOC values in terms of *equivalent ton-mile* costs with units of US$/NM/t of payload.

A simplified DOC model proposed by TU Berlin (TUB) which also estimates equivalent ton-mile cost in units of €/NM/t of payload, is also presented for comparison. The US dollar to Euro conversion of 1.29 US$/€ was chosen.

Table 4 - Direct Operating Cost Method

Euros €	**Current A320**	**C-WING**	**Difference**
AEA	1.2483	1.1700	- 6%
TUB	1.1114	1.0429	- 6%
US $			
AEA	1.6136	1.5125	- 6%
TUB	1.4367	1.3481	- 6%

8. SUMMARY AND CONCLUSIONS

The aim of the project was to study the efficiency of a novel non planar wing concept, "C-Wing". The study was executed through a sizing method, and by estimating induced drag calculations.

Firstly, a sizing analysis for current Airbus A320 (planar wing) aircraft was performed using a preliminary sizing method to ensure the approximate results comparing with the available data. It was shown that the percentage difference between available A320 parameters and calculated values were less than 2%. These close approximations implied the sizing method was competent to perform sizing analysis for aircraft with C-Wing configuration, whose parameters would then be compared with previously calculated A320 aircraft results. This comparison would depict the efficiency of the novel C-Wing concept. The calculations showed that considerable mass savings for take-off, landing and operational empty mass were obtained for nonplanar wing configuration. In addition, substantial difference in mission fuel fraction savings and take-off thrust of an engine were obtained between existing A320 and aircraft with C-Wing configuration. The new configuration also adopted the wing span constraint of 36m. Together with the reduced wing area the aspect ratio increased. These factors play a big role in reducing the induced drag as can be seen from the equation. It can also be hinted that a rubber engine option was considered for this configuration. This differences meant large mass and fuel savings for the same mission which ultimately leads to 16% less fuel mass and 6% lower operating costs!

Secondly, the importance of the C-Wing concpet was described by calculating the Oswald efficiency factor (span efficiency factor). The calculations were based on the vortex lattice method composed by Grasmeyer and on an general equation based on literature respectively. The dimensional form of drag equation shows that induced drag depends on speed, wing span and Oswald efficiency factor. Due to constraints on wing span, one possibility to reduce induce drag is to obtain high values for the Oswald efficiency factor. The results thus obtained from idrag computations were fitted to box wing equation (14) and to the winglet equation (15) to calculate the induced drag factor $k=1/e$. Figure 10 shows the results. The best fit for the idrag values calculated for the C-Wing was obtained with the box wing equation (14). The span efficiency value of 1.45 from Kroo's literature for h/b ratio of 0.2 showed a much lower induced drag factor compared to idrag computations and could be consider as too optimistic.

Finally, costing analysis for existing A320 and aircraft with C-Wing configuration was conducted using Direct Operating Cost (DOC) method employed by AEA and using TUB respectively. The costs difference between the C-Wing and existing A320 aircraft was about 6%. This implied that the equivalent ton-mile cost (units: €/NM/t and $/NM/t) for aircraft with C-Wing was6 % lower than for existing aircraft with planar configuration. This implication indicates immense reduction in aircraft costs.

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