Aerodynamic Analysis of C-Wing Aircraft

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Abstract: *In the recent years, the researchers focused on the development of long-range aircraft with the commercial aid of nonconventional design concepts. The C-wing concepts for large aircraft are highly preferred to overcome the design constraints such as span, aspect ratio, and compatibility. The span efficiency of the C-wing is approximately equal to that of the closed wing and hence a greater reduction in vortex drag is obtained than in the case of the planar wing. The flutter speed characteristics of the C-wing are investigated using Computational Fluid Dynamics (CFD) solver and the C-wing is retrofitted to the A340-200 aircrafts. In the CFD analysis the Navier Stroke equations are obtained as governing equations and structural vibration frequency is calculated by a Computational Structural Dynamics (CSD) solver. In addition, multi-grid technique is used to compute the aerodynamic forces with better accuracy. The proposed aeroelastic analysis consists of a partial coupling of CFD and CSD solvers. In the aerodynamic analysis, theoretical results show that there is a 20% of drag reduction for the C-wing as compared to the conventional wing. The numerical results for the sections of the C-wing are validated by using the experimental results of the NACA report.*

Key Words: *Flutter, CFD/CSD, C-wing, Horizontal winglet, Multigrid technique*

1. INTRODUCTION

Currently, most aerospace industries around the world have begun research into the development of a high-capacity passenger subsonic commercial aircraft. Designing conventional airplanes is difficult due to FAA rules. Wings play a vital role in large aircraft, making it more complex to design larger aircraft with a conventional design. The final conclusion is that basic aerodynamics and structure does not limit the size of aircraft that can be operated economically. Issues such as airport compatibility, scheduling, passenger loading and servicing, emergency outlet, and other practical considerations are, most likely, the principal concerns.

The significant area for improving the efficiency of modern transport aircraft has been in need of investigation and development of the non-planar wing tips. The drag consists of parasite drag and induced drag, which consumes more energy and fuel. The lift-induced drag typically comprises up to 90% of the total drag in climb and cruise mission due to the high lift coefficients [1]. The idea of using the final plates to increase the efficiency of wings first

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appeared in the 19th century in Hemke [3], and Mangler's [4]research. Both researchers exemplify that the lessening of induced drag with compromising of increasing the viscous drag due to increase in wetted area .Whitcomb established nonplanar wing tip device as winglet to produce significant side force to deploy the inflow and out flow. A various number of wing tip designs have been investigated using the Lanchester-Prandtl Lifting Line theory [13] and potential methods, their relatively low computational cost made them a popular choice. These methods can be successfully applied to induced drag analysis as the aircraft vortex sheet structure that leaves the trailing edge is independent of viscosity provided there is no separation [14].

Kroo [5] developed a more advanced wing weight model and viscous drag into his studies, coupled with traffic plane theory, which revealed the ‘Prandtl’ or boxes wing to be the efficient morphology for a given height, span, lifts, closely followed by a ‘C wings’ and winglets. For the C-wing, the described study states the effect of geometrical parameters of C-wing wingtip and the flow mechanism of drag reduction based on CFD techniques [8]. Moreover, a multidisciplinary optimized design of C-wing, which excluded the aeroelastic consideration, and drag characteristics of optimally span-loaded C-wing were investigated intensively [9, 10].

Cui Peng [14] investigated the flutter characteristics of the winglet and C-wing; the results shows that the 19% reduction of flutter speed over the conventional wing.

This paper deals with the C-wing concept retrofitted to the A340-200 aircraft. For the C-wing design, a suitable method is carried out from the previous research. The effect of taper ratio and the twist is added to the horizontal winglet as it improves the lift distribution and reduces the root bending moment over the wing. Naveen [15] investigated the C-wing configuration for PAV and shows similar results of others researchers.

The aerodynamic analysis is carried out at a cruising speed for wide-ranging angles of attack from -12 to 15 degrees. For analyzing the structural, the modal analysis method is used to find out the frequencies and evaluate the similarities and difference with the results with of planar wing. The effect of mass and aerodynamic flow over the horizontal surface on the wing is analyzed separately. This paper concludes there is a 20% reduction of induced drag when retrofitting the C-wing modal to the transport aircraft. The frequencies are much lower for the C-wing due to the structural mass and Static stable in nature

2. AN ANALYTICAL METHOD TO FIND OUT INDUCED DRAG

2.1 Prandtl’s Lifting Line Theory

Prandtl lifting line theory describes the theory of flow over the wing. It states that low pressure over a finite wing could force the air to roll over and around the tip, pushing the flow over the wing to move inboard and similar to the air under the wing to move outboard. In effects of a difference in span wise velocity which causes the air to roll up into a several stream wise vortices influencing the lift force along the span.

For multiple lifting surfaces, the induced drag equation modifies to

$$D_i = \frac{L_1^2}{\pi q b_1^2} + \frac{L_2^2}{\pi q b_2^2} + \frac{2\, L_1 L_2 \sigma}{\pi\, q\, b_1 b_2} \tag{1}$$

Where σ indicates the interference coefficient and the above expressions are in the assumption of elliptical lift distribution over the wing otherwise the effect of Oswald efficiency factor “e” is added in each term in the above expression.

2.2 Kroo's Method

Dr. Kroo proposed a method to explain the .minimum induced drag span load over the wing by a secondary loaded lifting surface. In order to label the downwash velocities induced by a secondary lifting surface on the wing, an analytical methodology given by von Kármán and Burgers was applied

$$D_i = \frac{L_1^2\sigma^*}{\pi q b_1^2} + \frac{L_2^2}{\pi q b_2^2} + \frac{2\,L_1 L_2 \sigma}{\pi\, q\, b_1 b_2} \tag{2}$$

where

$$\sigma = \frac{4I_{12(1)}}{\pi\,(b_1/b_2)^2} \tag{3}$$

$$\sigma^* = 1 - \frac{16}{\pi\,(b_1/b_2)^2}\sum_{3}^{N}\frac{I_{12(n)\hat{}2}}{n} \tag{4}$$

$$I_{12(n)} = \int_0^1 \left(\frac{\omega_{12}}{\omega_{01}}\right)\, sin\,[n\,(cos^{-1}y)]dy \tag{5}$$

3. COMPUTATIONAL APPROACH

In the Fluid-Structure Interaction (FSI) problem, aeroelasticity involves the coupling effect of steady aerodynamics and structural vibration.

This effect, from a viewpoint of governing equation, is characterized by compatibility and equilibrium conditions that are imposed on the FSI interface. Therefore equations and boundary conditions of an aeroelastic system in the form of

$$\mathrm{M}\,\ddot{X} + \mathrm{C}\,\dot{X} + \mathrm{K}\,\mathrm{X} = \mathrm{P(t)} \tag{6}$$

Eq. (3) is the Euler equation written in an integral form to describe inviscid airflow, where ***W*** and ***F*** are conservative variables and advection fluxes, respectively.

Eq. (2) is the structural equation of motion, where ***M***, ***C*,** and ***K*** denote mass, damping and stiffness matrices, respectively, and ***P (t)*** is a vector of external aerodynamic loads.

Whereas Eq. (3) gives the conditions of displacement compatibility and force equilibrium.

Time marching technique in coincidence with a partitioned procedure is the general approach to obtain responses of an aeroelastic system.

4. DESIGN METHODOLOGY

The design for a very large aircraft used the C-wing configurations from the McMasters [12] methodology.

With the help of above methodology the suitable design has chosen for retrofitting concept for passenger aircraft was quite cumbersome during the process.

This paper deals with the retrofitting of a C-wing concept which is applied to an Airbus-A340-200 aircraft using a far less complex design structure as shown in fig. 1.

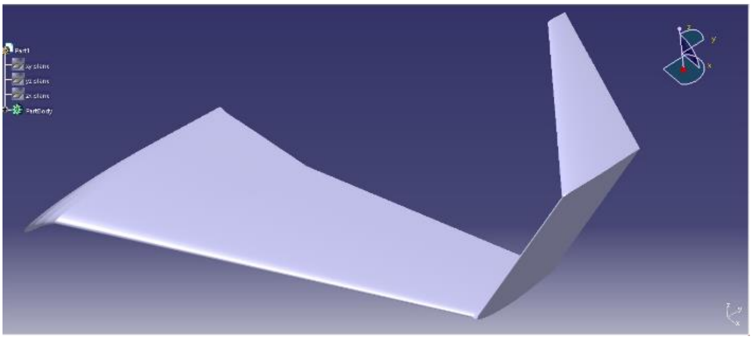


Fig. 1. C-wing model

A symmetrical airfoil NACA six series has been used for the main wing box and vertical winglet. The horizontal winglet uses NACA 0012 airfoil with a twist angle of 1 degree.

5. AERODYNAMIC MODEL

In CFD analysis, as per earlier researches, it is confirmed that inviscid flow model was applicable to an aero elastic simulation for wings with high-aspect-ratio that operates at the low angle of attack [3, 8].

Correspondingly, the Navier stoke equations include flow viscosity which was employed for models to have steady aerodynamics during turbulence. Advection scheme is used in CFD for numerical discretization, which can be cast in the form

$$\frac{\partial \rho}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=0 \tag{7}$$

The turbulence is a K-ε model for compressible turbulence flow involving mean flow separation.

6. FLUID STRUCTURAL COUPLING

The necessary simulation was advanced through a sequence of FSI time steps, each of which consisted of several stagger iterations. During the stagger iteration, responses of fluid and structure were derived using CFD and FEM technologies separately, and the coupling effect was accounted for in the form of bi-directional load transfer (force and displacement). An implicit solution of the FSI problem can be achieved by using this procedure with a reduction of any temporal lags in the system response that may exist. If the time step was sized appropriately iterations were required for the convergence of load transfer.

During most of the realistic applications, CFD and FEM grids were discrepant at the interface. The load transfer involved an interpolating process that played an important role in FSI modeling and analysis accordingly.

Fluid and structure are the two issues that match the situation of the interface and interpolating method and were tied to the exact coupling between different domains. In order to avoid the mesh alignment error, outer surfaces of the wing model (namely, the interfaces) were formally divided into three parts, namely the upper, lower and tip-end, where separate interpolations were conducted.

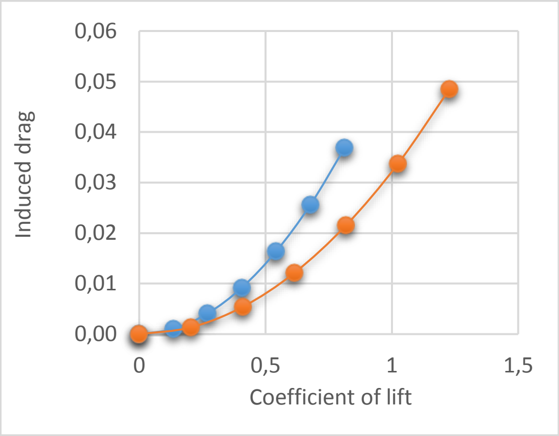
The accuracy and stability of an aero structure coupling were well-maintained by the above-mentioned stages that precisely complete the data exchange.

7. RESULTS AND DISCUSSIONS

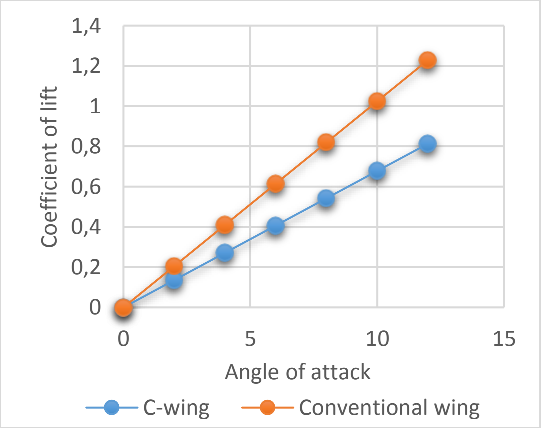
7.1 Theoretical results

In reference to the theoretical analysis, the aerodynamic coefficients can be found from the experimental results by NACA report [11] at corresponding Reynolds no. Prediction of the aerodynamic coefficients for the complete section can be predicted individually by using aerodynamics equations (1).

Induced drag for the conventional wing and C-wing can be determined by using Prandtl lifting line theory for multiple lifting surfaces. In the Prandtl theory, the effect of downwash of each individual velocity vector influenced the lifting surfaces. From the Prandtl graph for multiple lifting surfaces, an interference factor can be predicted that also influences the lifting surfaces amongst each other.



(a)



(b)

Fig. 2. (a) & (b) represent the theoretical aerodynamic coefficients for C-wing and conventional wing

The graphs in fig 2 (a) and (b) shows the similar results to the previous literature, clearly indicating that the induced drag is lesser for the C-wing when compared to the winglet. The reduction is approximately 20% of the conventional wing, but the theoretical results show that 60-70% of the total effect of the C-wing induced drag as it is three-dimensional phenomenon which it is entirely based on the vortex strength, downwash velocity etc.

Due to the influence of the various variables, the actual interference cannot be interpolated in theoretical expression. It can be predicted by the using of high fidelity computer algorithms and also by various in wind tunnel test.

7.2 Numerical simulation

For the simplification of analysis, the C-wing has been divided into three sections as shown in fig 3. The suitable mesh is carried out by choosing domain across the airfoil which predicts boundary layer effects. The grid points are accelerated and results are computed using the Multi grid technique.

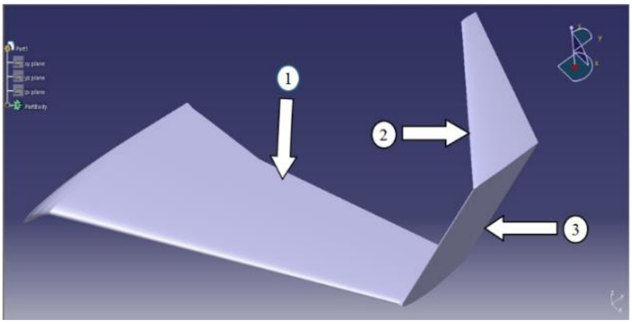


Fig. 3. Splitting the sections of C-wing

The CFD analysis is carried out to find out the aerodynamic characteristics of the C-wing at cruising speed and cruising altitude with appropriate boundary conditions at that altitude.

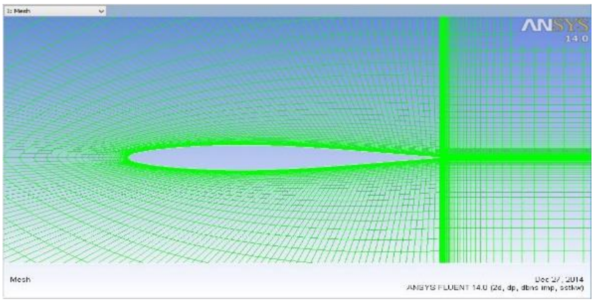
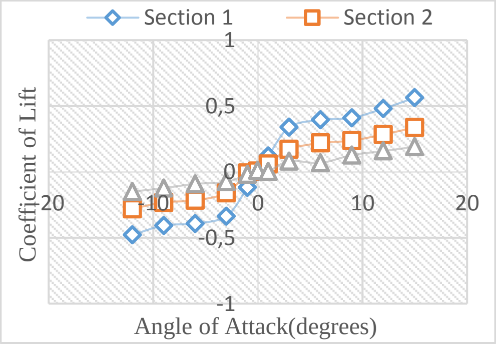
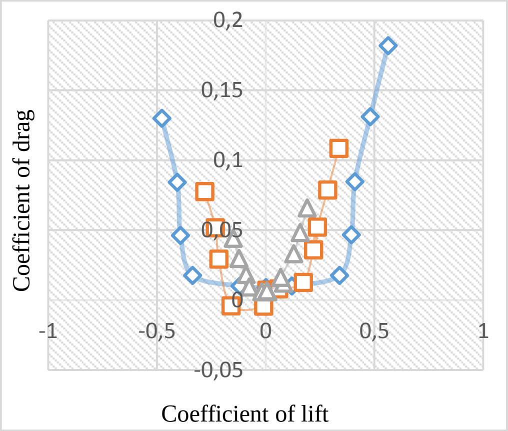


Fig. 4. The Mesh of Section 1

From the above graph in fig 5, it can be concluded that numerical results do match with the experimental results validating the NACA report (11)



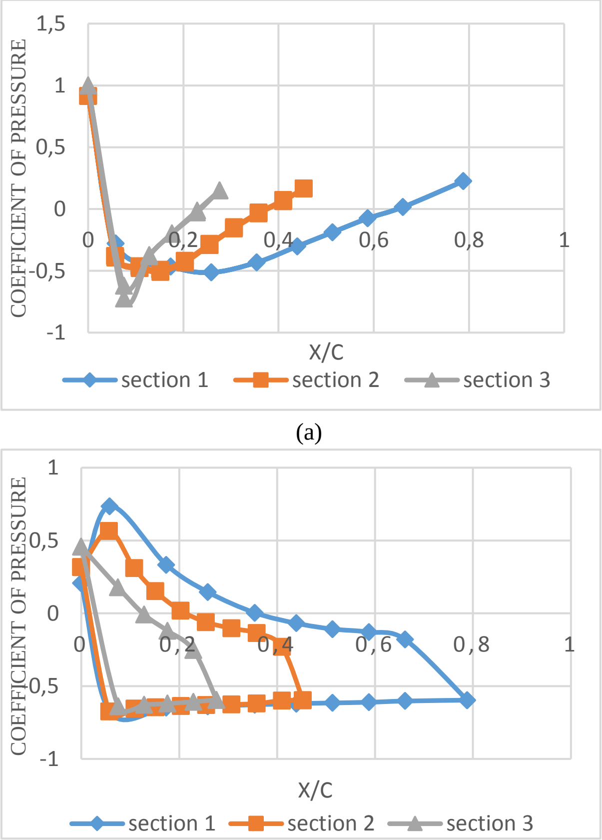
(a)



(b)

Fig. 5. (a) and (b) represent the numerical results of aerodynamic coefficients for various sections of C-wing

The graph in fig 6 (a) and (b), shows the pressure distribution for the various sections of the C-wing in terms of coefficient of pressure. For a symmetrical airfoil, there will be a null lift at zero angle of attack, whereas section 3 shows lift production; this can be clearly understood from the above graph due to the pressure difference between the upper and the lower surface of the wing.



(a)

(b)

Fig 6. Pressure distribution for various sections of the C-wing at (a) α=0, (b) at α=15

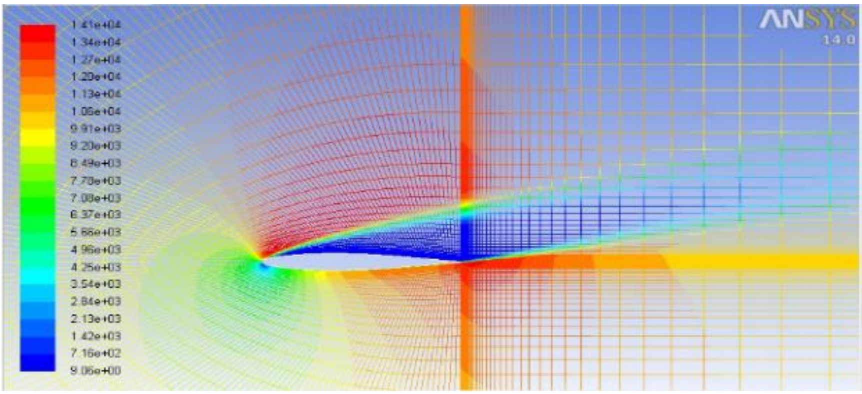


Fig. 7. Contour diagram for dynamic pressure at α=12 degree for section 1

From the modal analysis, it shows that the exciting frequency for the C-wing is much lower than that of the conventional wing. In the previous researchers there a flutter speed reduction of up to 19% over the conventional wing. The mass of the C-wing influences the flutter speed than aerodynamic effects of the horizontal winglet of the proposed wing.

8. CONCLUSIONS

From the literature survey, it can be understood that the C-wing shows a better advantage over reduced induced drag, aspect ratio than the conventional design for large aircraft. Due to “C”, shape an additional lift force can be obtained in the horizontal winglet which too can be used as control surface as well.

The C-wing configuration is designed using McMasters, JH (12).A symmetrical airfoil with taper ratio and twists are used for horizontal winglet for additional lift force and performance. To simplify the analysis the model is divided into three sections such as a plain wing, vertical winglet, and horizontal winglet.

The Multi grid technique is used to compute aerodynamic forces with better accuracy using CFD solver for analysis. The Navier Stroke equations are obtained as governing equation. The analysis is done for the various angles of attack at the cruising speed. From the graph, it results that the lift force is produced at the zero degrees angle of attack for section three, because of the influence of twist and taper ratio.

The mass of the horizontal winglet of the C-wing that influences the structural behavior and flutter speed when considering the aerodynamic effects on structural analysis.

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