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Design and Analysis of a Box-Wing

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Abstract*— This paper highlights how the aerodynamic nature and performance characteristics of an aircraft can be enhanced by using a box-wing configuration rather than the conventional wing configuration due to its capability of producing a very low amount of induced drag. An aerodynamic investigation is performed by first designing a box-wing configuration on a reference aircraft and then analyzing it using CFD tools in ANSYS, Inc. software. Comprehensive mesh generation and grid convergence studies were performed on this model to minimize the error in the solution. Detailed CFD studies were also performed by gathering the results obtained from the solution. Certain performance parameters of the aircraft like glide ratio, fuel efficiency, range and endurance can be calculated for the box-wing configuration. It has been observed through the aerodynamic analysis using FLUENT that the box-wing configuration reduces the drag on an aircraft considerably which contributes positively towards an aircraft's performance. The structural and manufacturing feasibility of using such a configuration for wings, however, is highlighted as well and further research is recommended for future aircraft design.

I. Introduction

This paper analyses the aerodynamic advantages which a box-wing configuration offers over the conventional wing configuration. The computational as well as mathematical analysis is performed for comparative purposes to get an idea on the subject of drag reduction. Passenger and cargo aircrafts are estimated to grow by a factor of two or three in the next two decades, especially along medium and long range routes worldwide. There is an increasing demand in the aeronautical industry for more fuel efficient aircrafts. A 1% reduction of drag for a large transport aircraft, saves 400 liters of fuel [1]. The industry is working on many novel concepts and unconventional designs for future more fuel efficient aircrafts. Replacing the conventional wing with a box-wing of same planform area is one of those concepts. This concept was first proposed by L. Prandtl in 1924 [2] and, to honor his work, is also sometimes referred as "Prandtl Plane." The total drag on an aircraft, during cruise phase, mainly consists of skin friction and induced drag with induced drag relatively lower than the skin friction drag. But still it consists of 43% of the total drag [3]. Thus any reduction in induced drag will directly improve the efficiency of the overall design. The box-wing may, however, be about twice as heavy as the conventional wing of same area. A lighter fuselage or using a composite material with high strength to weight ratio is proposed to tackle this problem [5]. It has to be noted that any concept related to performance improvement in aerodynamics comes with a wide range of side effects. An optimum compromise is agreed first, before manufacturing a new design. Lockheed Martin is one of the companies which is working on box-wing. It has studied this concept for three decades, but has been waiting for some lightweight composite materials, landing gear technologies, hybrid laminar flow advancement and other tools to make it a feasible wing configuration. This design is among those presented to NASA at the end of 2011 by companies that conducted NASA-funded studies into aircraft that could enter service in 2025.

II. Methodology

For evaluating and comparing the performance of a box wing aircraft it is necessary to define a reference aircraft. The box wing aircraft is based on Airbus A320-200. Both of the aircrafts have the same design mission which allows for comparing their performance. For a clear comparison both aircrafts have the same wing span and total wing reference area. The data for the reference area is taken from published information [4].

In this study, only wing geometries have been computationally analyzed not the whole aircrafts. Wing is the primary lifting surface on an airplane and the reduction of induced drag can be observed by looking at the CFD simulation results of the wing only. Reasonable approximations have been made, by referring to the literature, which allowed the calculation and comparison of certain performance parameters. Again, this analysis is only for comparative purpose to give the readers and authors basic insight about how the aerodynamics of a conventional wing differs from the aerodynamics of a box-wing designed for exactly the same mission requirements.

A. The Design

The box-wing geometry has been designed keeping in view the aerodynamics, stability, and structural factors mentioned in Ref. [4]. The airfoils for both of the wings was also kept same keeping in view the design lift coefficient requirements. The Box-Wing design mentioned in Ref. [4] was taken as a benchmark case as the author recommended further computational analysis for detailed flow studies. PTC Creo [11] software is used for creating the CAD model of both of the wings while CFD calculations are performed on FLUENT module of ANSYS, Inc. [10] software.

B. Mesh Generation

The first step after modelling, in both cases, was to create a suitable and good quality mesh of the far-field domain. A comprehensive grid convergence analysis was performed to ensure the accuracy because of the computational power limitations.

C. *Flight Conditons and Boundary Conditions*

The flight conditions for analyzing both of the wings were defined exactly the same i.e. Altitude of 35,000 ft., Cruise Mach of 0.76 and an angle of attack of 2.5 degrees [4]. The boundary conditions “Pressure far-field” and “Symmetry” were used to define the flight conditions in FLUENT. For turbulence modeling, k-epsilon model with standard wall functions is used. K-epsilon (k-ε) turbulence model is the most common model used in Computational Fluid Dynamics (CFD) to simulate mean flow characteristics for turbulent flow conditions [6]. It is a two equation model which gives a general description of turbulence by means of two transport equations (PDEs). The original impetus for the K-epsilon model was to improve the mixing-length model, as well as to find an alternative to algebraically prescribing turbulent length scales in moderate to high complexity flows. The performance calculations and relations are formed using the existing literature.

III. WING MODELLING

Having clearly defined the design mission parameters of a reference aircraft, the airfoil was selected on the basis of design lift coefficient and thickness to chord ratio ration. NACA 63-713 was selected for the design of both the wings.

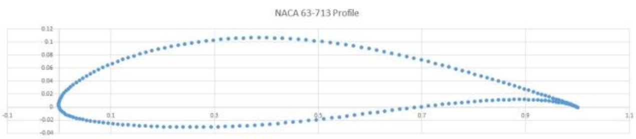

Fig. 1. NACA 63-713 Airfoil Profile

A. *The Box-Wing*

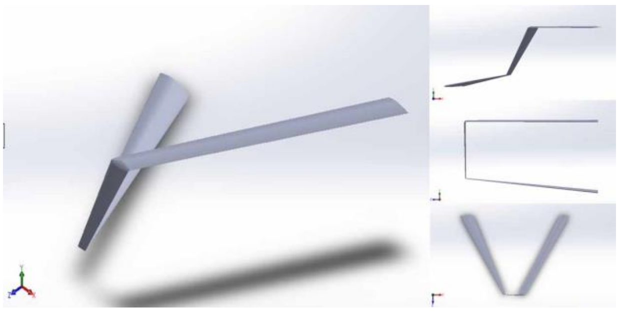

Fig. 2. The box-wing half geometry designed in Solidworks

The geometry was modeled in half because of its symmetry. There is a provision of symmetrical boundary condition in FLUENT, in which all the gradients normal to the symmetry plane are zero. That helps in reducing the computational cost.

The vertical winglets have the aerodynamic twist such that the lift distribution comes out to be according to Ludwing Prandl’s theory of optimum lift distribution for box-wings. [2]. It is shown in Fig. 3.

B. *The Conventional Wing*

Using the published information [4] about the airbus A-320-200 aircraft, the wing was modeled according to the given dimensions. Note that the reference are of both of the wings is

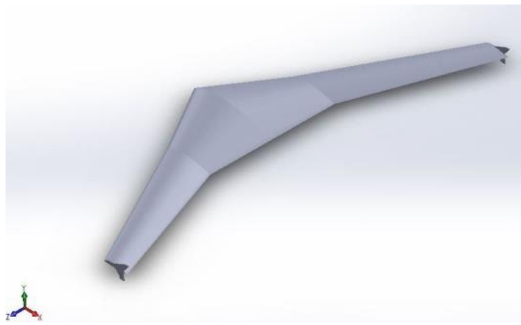

Fig. 4. The Conventional Wing

kept exactly the same. i-e 122.6 m^2. It is shown in Fig. 4.

IV. BOX-WING COMPUTATIONAL ANALYSIS

Mesh has been created using ICEM CFD mesh module in ANSYS Inc. First of all, a suitable semi-spherical far-field domain for the wing was defined in ANSYS Design-modeler. Proximity and curvature type size function was used to create a mesh which can capture the wake region. A total of 4 meshes (depending upon the number of elements) were taken into account to ensure the grid convergence. And hence the required results i-e the lift and drag coefficients were compared for all types of mesh sizes.

Grids and Number of Elements	
Mesh No.	***No. of Elements***
1	0.12 million
2	0.19 million
3	0.38 million
4	0.78 million

Table 1. Grids and Number of Elements

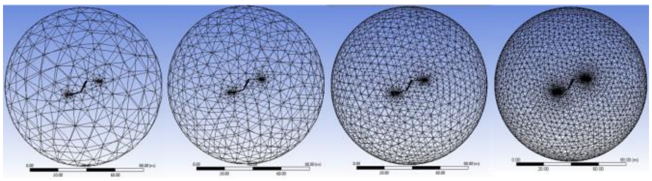

Fig. 5. Four Meshes Having Different Element Numbers

Taking a look at the zoomed-in view of the mesh having the highest number of elements at a cut plane (Fig. 6), one can recognize its hybrid nature. The elements far off the wall are unstructured (tetrahedral layers) whereas the close to wall region has structured elements (the prism layers). These structured elements help us to accurately capture gradients in the boundary layer region.

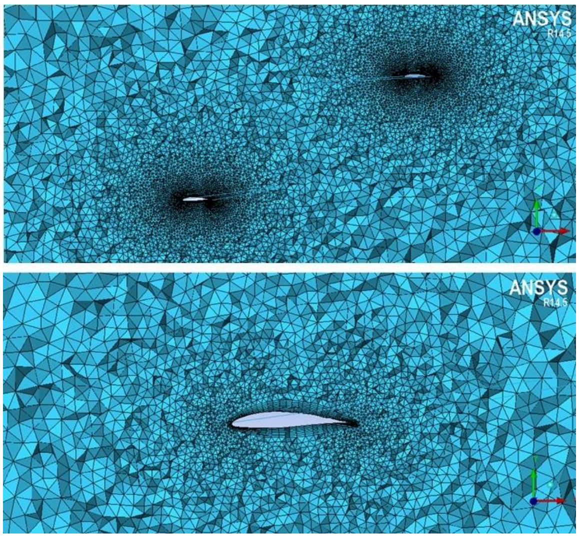

Fig. 6. Zoomed in view of the Hybrid Mesh

A. *The Mesh Quality*

For having accurate simulation results, the mesh quality needs to be ensured as well. The graph in Fig. 7 shows the overall element quality of the mesh with highest number of elements. The quality values shown in the fig. 7 tell us that most of the elements lie in the good quality region. And almost all of them lie in the quality values of greater than 0.5. Elements having quality 1 are the best and having the value 0 are the worst.

B. *Aerodynamic Analysis*

The solution was calculated using FLUENT. The monitors used while ensuring the convergence are Lift Coefficient (C_L) and Drag Coefficient (C_D). The converged values of Lift & Drag coefficients at the cruise phase of flight were observed for all mesh types and compared.

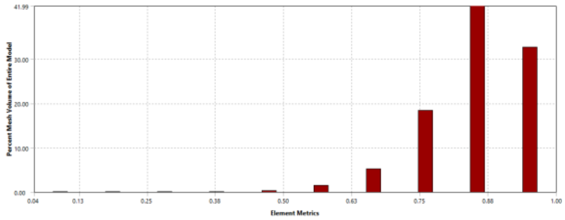

Fig. 7 Mesh Element Quality

Mesh No.	C_L	C_D	C_L/C_D	% difference C_L	% difference C_D
1	0.3117	0.0178	18.534	0	0
2	0.3535	0.0172	20.513	6.75	3.55
3	0.3768	0.0169	22.194	6.58	1.48
4	0.3717	0.0164	22.804	1.35	3.99

Table 2. The Aerodynamic Values

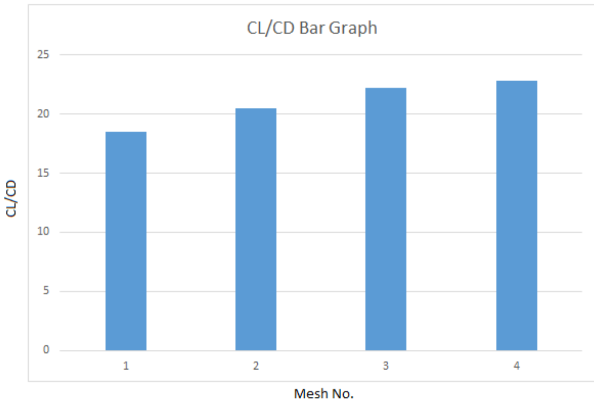

Fig. 8. C_L/C_D Comparison

Fig. 8 shows the comparison between the obtained values of CL/CD from every type of mesh. It is also referred as the glide ratio. We can clearly see the convergence of these coefficients from Table 2 and Fig. 8.

C. *Computational and Analytical Results*

I) The Lift Distribution

The computational analysis showed the acquisition of required Prandtl's optimum lift distribution over the box wing and the vertical winglets as well as shown in Fig. 3. The lift distribution over the designed wing can be observed clearly in Fig. 9.

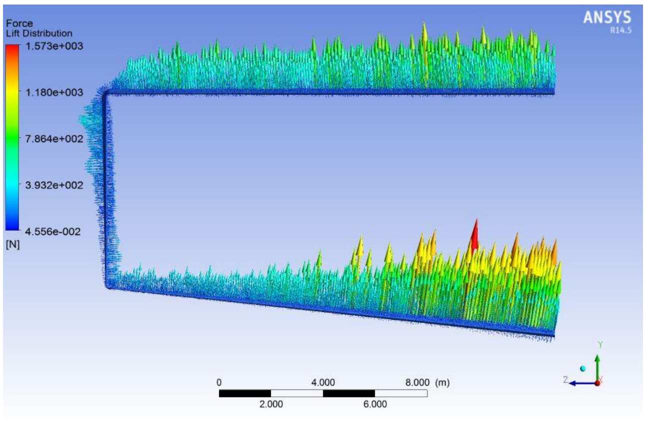

Fig. 9. The Lift Distribution on the Box-Wing

II) The Definition of planes

For comprehensive analysis, three planes at three different locations away from the fore-wing leading edge in positive x-direction (the wing wake) were defined.

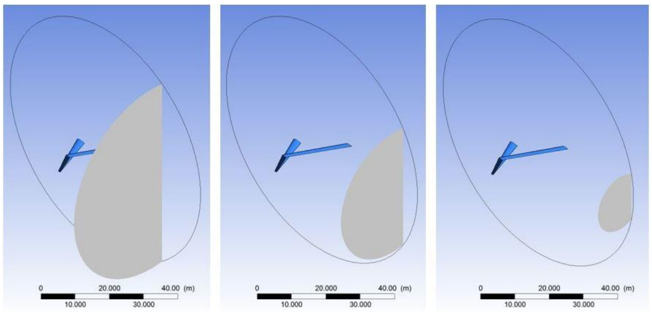

Fig. 10. Three Locations in Wing-Wake

The three locations are at 25, 35 and 50 meters away from the wing leading edge respectively. These planes in these locations are named as plane 1, 2 and 3 respectively.

III) Interference between Fore and Aft Wings

To observe the interference between the fore and aft wings of the box-wing aircraft, the velocity contours in the wing wake region at planes 1, 2 and 3 were observed. The interference would lead to interference drag which is undesirable.

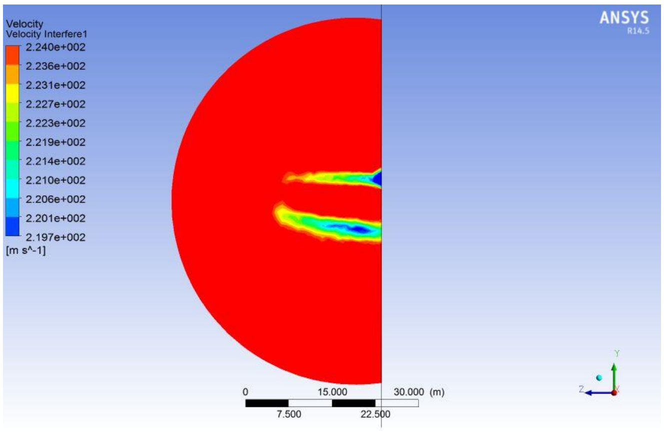

Fig. 13. Velocity Contours at Plane 1

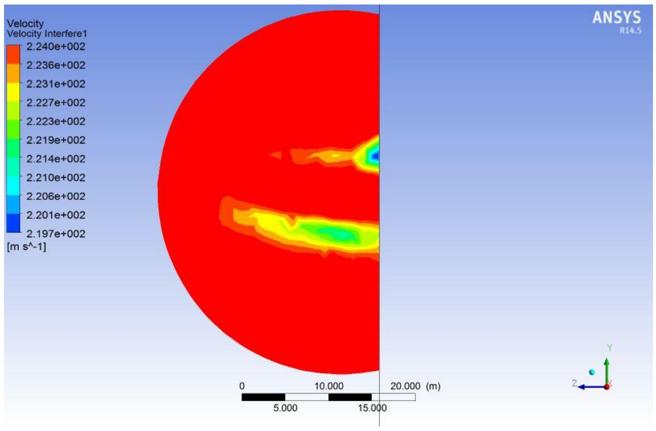

Fig. 11 Velocity Contours at Plane 2

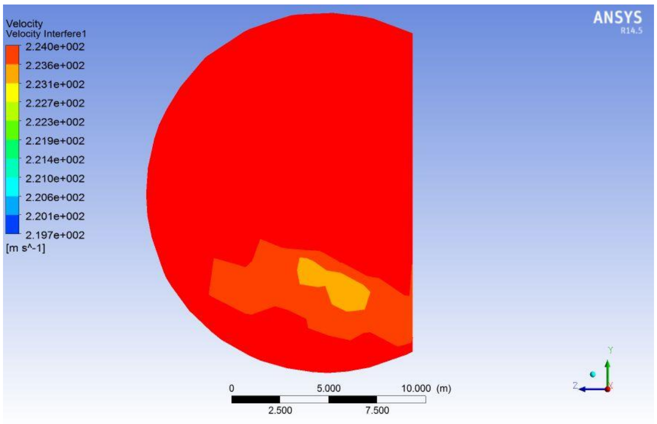

Fig. 12. Velocity Contours at Plane 3

The interference studies shown in figures 11 to 13 show that no drag is being produced because of the flow interference in the present case of Box-Wing aircraft.

The flow interference also depends on the lift ratio between the two wings. Prandtl [2] suggested that to have minimum interference drag, the lift ratio between both of the wings must be unity.

Fig. 14 is the graph plotted using Prandl's equation of induced drag for a biplane. [2], [4]. It shows how the unequal lift over the two wings would lead to an increase in drag. The Graph was plotted for different values of h/b ratios. h/b is the ratio of winglet height to wingspan and this value plays a critical role in the definition of interference drag. For the present case of box-wing study, the h/b value is 0.22. D_i is the induced drag for a real case with unequal lift distribution over the two wings and $D_{i(min)}$ is the ideal induced drag in ideal case where the lift values are equal.

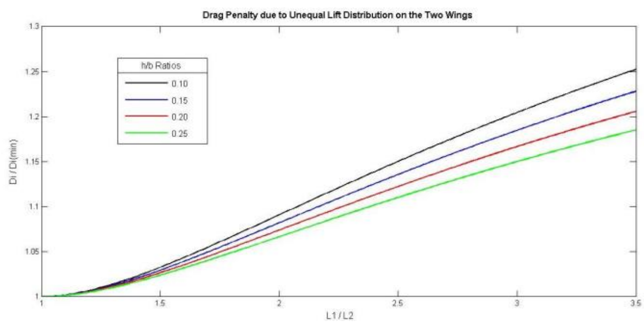

Fig. 14. Drag Penalty for Unequal Lift Distribution

IV) The Vorticity Magnitude

For the studies of minimizing induced drag, vortex flow must be observed in the wing wake. The contours of vorticity magnitude are shown in figures 15 to 17 at all the 3 planes defined earlier.

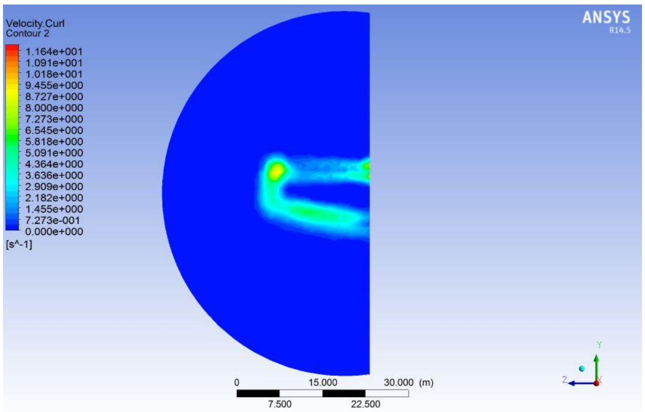

Fig. 15. Contours of Vorticity Magnitude at Plane 1

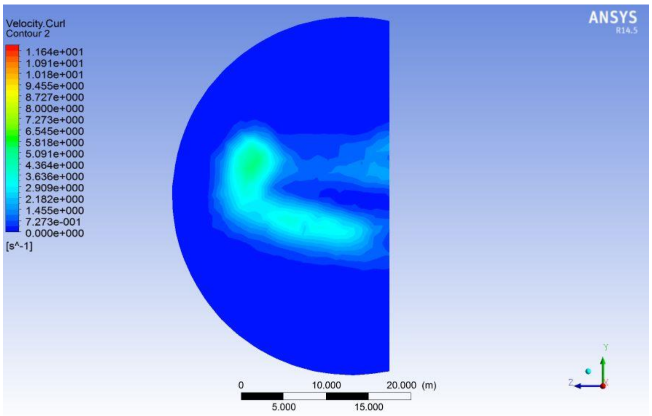

Fig. 16. Contours of Vorticity Magnitude at Plane 2

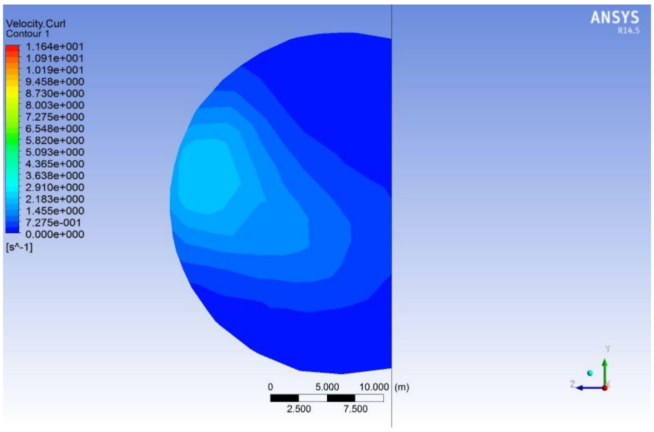

Fig. 17. Contours of Vorticity Magnitude at Plane 3

V. Conventional Wing Computational Analysis

The whole computational process for the reference wing is also repeated. The grid convergence was made sure as well.

I) The Vorticity Magnitude (Reference Wing)

For a clear comparison only the vorticity magnitude values are shown since the induced drag depends on the magnitude of vorticity developing at wingtips majorly. The contours are shown in figures 18 to 20 at the planes in wing wake defined exactly at the same positions as the Box-wing.

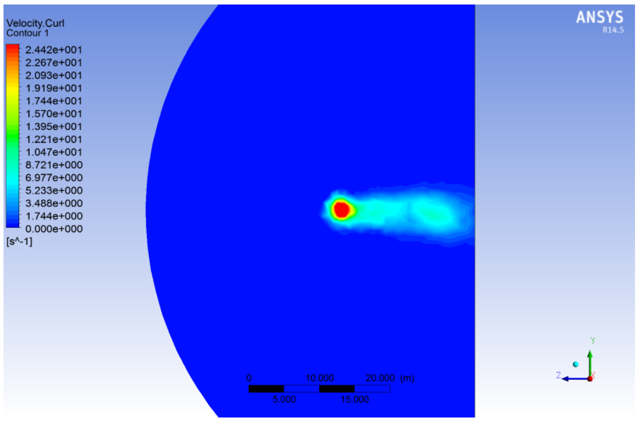

Fig. 18. Contours of Vorticity magnitude at Pane 1 (Ref-Wing)

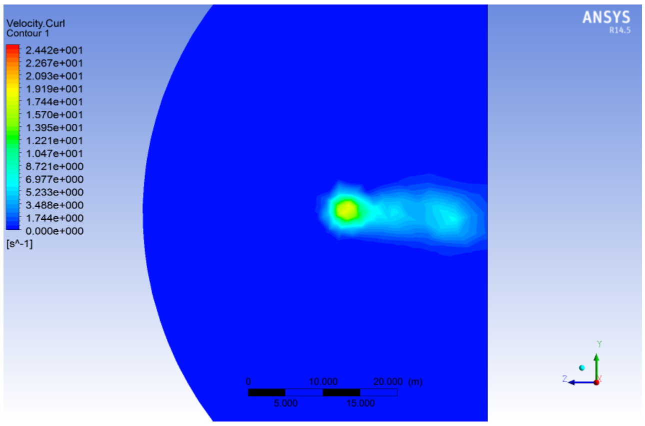

Fig. 19. Contours of Vorticity magnitude at Pane 2 (Ref-Wing)

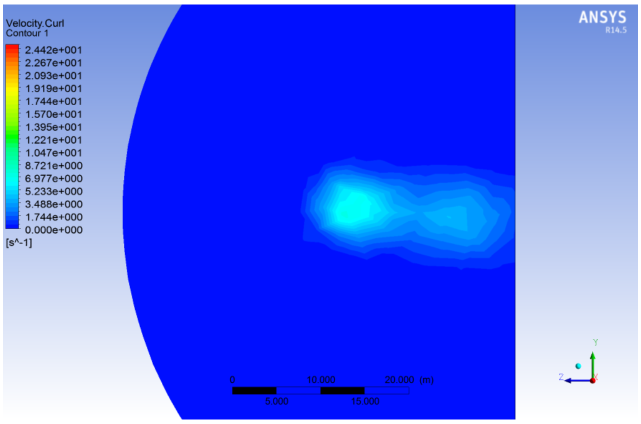

Fig. 20. Contours of Vorticity magnitude at Pane 3 (Ref-Wing)

In the figures 15 to 20, there is a very clear indication of reduction in the vorticity magnitude values for the Box-Wing and that implies a very low induced drag as compared to the reference wing. For the case of Box-Wing, the maximum value of vorticity magnitude at the closed plane 1 is around 8.7 sec^{-1}. For the case of conventional wing, the maximum value at the very same location is around 24.42 sec^{-1}.

VI. CONCLUSION

In this study only aerodynamic merits of box-wing configuration have been studied. It is observed that by replacing the box wing instead of a conventional wing configuration on the same aircraft having same span and same wing area, we get very less induced drag and hence a better glide ratio. For a detailed analysis and feasibility of such designs, detailed structural and stability analyses are recommended. No innovative idea in aerospace technology comes without a cost. Only after a multidisciplinary optimization, a new concept is accepted or rejected. It is the view of the author that since drag reduction directly makes an aircraft fuel efficient, such a concept can be realized with a few compromises in other disciplines.

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REFERENCES

[1] Schneider, W. W., “The importance of Aerodynamics in the development of commercially successful transport aircraft,” Aerodynamic Drag Reduction Technology. Proceeding of CEAS/DRAGNET European Drag Reduction Conference, Potsdam, Germany19-21 June, 2000, pp. 9-16J.

[2] Prandtl, L., “Induced drag of multiplanes” NACA TN 182, 1924.

[3] Frediani, A., “A 250 Passenger Prandtl Plane Transport Aircraft,” XVIII CONGRESSO NAZIONALE AIDAA. e. a. 2005.

[4] Schiktanz, D., and Scholz, D., “Box Wing Fundamentals – An Aircraft Design Perspective,” Deutscher Luft - und Raumfahrtkongress 2011, Document ID: 241353

[5] Pester, M., “Multi-Disciplinary Conceptual Aircraft Design Using CEASIOM,” Hamburg, Hamburg University of Applied Sciences, Department of Automotive and Aeronautical Engineering, Master Thesis, 2010.

[6] Versteeg, H., and Malalasekera, W., An Introduction to Computational Fluid Dynamics: The Finite Volume Method, 2nd ed., Pearson Education Limited, 2007.

[7] Khan, F. A., “Preliminary Aerodynamic Investigation of Box-Wing Configurations using Low Fidelity Codes,” Master Thesis, Continuation Courses Space Science and Technology Department of Space Science, Kiruna, Luleå University of Technology, 2010.

[8] Anderson, J. D., Aircraft Performance and Design, 1st ed., McGraw Hills, 1998.

[9] Raymer, D. P., Aircraft Design: A Conceptual Approach, 2nd ed., AIAA Inc., 1992.

[10] ANSYS, Inc., Software Package, Ver. 14.5, SAS IP, Inc. 123 E 17th St Cheyenne, WY 82001 USA, 2012.

[11] PTC Creo, Software Package, Ver. 2.0, PTC Corporate Headquarters 140 Kendrick Street, Needham, MA 02494 USA, 2012.

[12] Paul O Jemitola, John P Fielding, “Box Wing Aircraft Conceptual Design”, 28th international congress of the aeronautical sciences, 2012.+

[13] L. R. Miranda, “Boxplane wing and aircraft” US Patent 3,834,654, Sep. 10, 1974.

[14] J. Wolkovitch, “Joined Wing Aircraft”, US Patent 4,365,773, Dec. 28, 1982.