Design Optimization of a Ducted Fan Blended Wing Body UAV using CFD Analysis

Melvin Philip [1], Venkatesh Kusnur [2], Prashant Manvi [3]
[1,2,3]Assistant Professor, Department of Aeronautical Engineering,
ACS College of Engineering,
Bangalore, India-560074

Abstract: **— This project work begins with an overview of various Blended Wing Body aircraft designs in relation to their aerodynamic behaviour. After a preliminary analysis of the ideal aerodynamic performance for the baseline configuration, flow analysis is done to investigate the aerodynamic performance of the baseline design. The emerging BWB aircrafts are mainly designed for a higher speed using Jet engines. This BWB concept is implemented in designing of UAVs for a lower Mach number, with a higher Lift to drag ratio. The UAV design considered in this work belongs to 1 kg class.**

Existing baseline model geometry is designed using CATIA V5 and analyzed using Computational Fluid Dynamics (CFD) packages. This model is then optimized using conventional optimizing technique for better performances. The Mach number range is kept constant and the whole design is optimized for getting the maximum L/D ratio. The optimization includes changing the parameters such as sweep angle, taper-ratio, wing twist, root and tip chord etc. Studies have carried out for models with and without winglets, and are analyzed.

The optimized model is then converted to a ducted fan configuration, for the VTOL characteristics. It is meshed in ICEM-CFD and analyzed in ANSYS CFX, with the inner domain containing the fan rotating, and the outer domain stationary. The loss of plan form area caused due to installation of ducted fan is compensated in optimized design. The cruise flying condition was analyzed at 15 m/s wind speed. The optimized design has a three degree twist at the tip chord. The model produced a normal force over the wing (lift) which satisfies the design cruise condition. The results are validated with the existing literatures.

Keywords— BWB, Ducted Fan, Lift, Drag, UAV, VTOL

I. INTRODUCTION

Aircraft technologies that could give greater performance include a large improvement in Lift-to-Drag ratio of a wing coupled to evolutionary improvement in composite structure and engines, such as Blended Wing Body aircraft configuration. This next generation airlifter has been researched with a high L/D ratio wing configuration design, engineered materials, composite fabrication and fastening, and next generation material for airframe and skin. A Blended-Wing-Body (BWB) design approach is to maximize overall efficiency by integrated the propulsion systems, wings, and the body into a single lifting surface. This BWB configuration is a new concept in aircraft design which expects to offer great potential to substantially reduce operating costs while improving an aerodynamic performance and flexibility for both passenger and cargo mission.

In recent years unconventional aircraft configurations, such as Blended-Wing-Body (BWB) aircraft are being investigated and researched with the aim to develop more efficient aircraft configurations, in particular for very large transport aircraft that are more efficient and environmentally-friendly [12] .The BWB configuration designates an alternative aircraft configuration where the wing and fuselage are integrated which results essentially in a hybrid flying wing shape. The first example of a BWB design was researched at the Lockheed Company in the United States of America in 1917. The Junkers G. 38, the largest land plane in the world at the time, was produced in 1929 for Luft Hansa (present day; Lufthansa). Since 1939 Northrop Aircraft Inc. (USA), currently Northrop Grumman Corporation and the Horten brothers (Germany) investigated and developed BWB aircraft for military purpose. At present, the major aircraft industries and several universities has been researching the BWB concept aircraft for civil and military activities, although the BWB design concept has not been adapted for civil transport yet. The B-2 Spirit, (produced by the Northrop Corporation) has been used in military service since the late 1980s. The BWB design seems to show greater potential for very large passenger transport aircraft. A NASA BWB research team found an 800 passenger BWB concept consumed 27 percent less fuel per passenger per flight operation than an equivalent conventional configuration (Leiebeck 2005) [12].

Conceptually, the main aerodynamic advantage of the new BWB design is its lower wetted area to volume ratio and lower interference drag as compared to the conventional aircraft. Indeed, an increase in (L/D) max of about 20% over the conventional design has been estimated for the blended wing body aircraft. However, these benefits can only be realized as an improved aerodynamic performance through careful and detailed aerodynamic shape design. Unfortunately, little is known regarding the best aerodynamic shape for BWB due to a large number of extra design variables and stronger coupling with the other disciplines such as structures and flight dynamics. On the aerodynamic performance side, as pointed out by Green [18] the maximum lift-to-drag ratio (L/D) max depends on the ratio of the aircraft span to the square root of the product of the induced drag factor and the zero-lift drag area, which is proportional to the wetted area of the aircraft. From this relation, one can see that larger span, smaller wetted area, lower skin friction (e.g. laminar flow technology), or less-induced drag can all potentially provide substantial improvement in aerodynamic performance.

II. OVERVIEW OF BWB PROJECTS AND LITERATURES

'N. Qin and A. Vavalle' (2004) [1] have presented an international paper which deals with the 'Aerodynamic considerations of blended wing body aircraft'. Viscous flow simulations were carried out to investigate the aerodynamic performance of the baseline design. The effects of span-wise distribution on the BWB aircraft aerodynamic efficiency were studied through an inverse twist design approach, combining both a low-fidelity panel method and a high-fidelity Reynolds-averaged Navier–Stokes solution method. Wirachman Wisnoe and Rizal Effendy Mohd Nasir (2009) [2] have conducted 'Wind Tunnel Experiments and CFD Analysis of Blended Wing Body (BWB) UAV at Mach 0.1 and Mach 0.3'. This work shows the Steady-state, three- dimensional Computational Fluid Dynamics (CFD) of the BWB at Mach 0.3 and Wind Tunnel experiments on 1/6 scaled half model of the BWB at Mach 0.1.

Toshihiro Ikeda (2006) [3] has done a research work on 'Aerodynamic analysis of BWBs' in which he has considered the large passenger aircraft with BWB concept. He assessed the aerodynamic efficiency of a BWB aircraft with respect to a conventional configuration, and to identify design issues that determine the effectiveness of BWB performance as a function of aircraft payload capacity. The approach was undertaken to develop a new conceptual design of a BWB aircraft using Computational Aided Design (CAD) tools and Computational Fluid Dynamics (CFD) software. Cengiz Camci and Ali Akturk (2010) [7] have done 'A computational and experimental analysis of a ducted fan used in VTOL UAV systems'. In this paper they discuss about the ducted fan properties. Ducted fan based vertical/short take-off and landing (VTOL) uninhabited aerial vehicles (UAV) are frequently used because they offer higher disk loading compared to open rotors and improve propulsive performance. A three-dimensional RANS based computational analysis is implemented for high resolution analysis of these systems under realistic operational conditions.

Osgar John Ohanian III (2011) [9] has published a PhD thesis titled ' Ducted Fan Aerodynamics and Modeling, with Applications of Steady and Synthetic Jet Flow Control' in which he explains the whole design and aerodynamics of ducted fan. This dissertation provides a new paradigm for modeling the ducted fan's nonlinear behavior and new methods for changing the duct aerodynamics using active flow control. Hui Wen Zhao (2009) [10] has submitted a thesis on 'Development of a Dynamic Model of a Ducted Fan VTOL UAV'. This work was based on an axial type ducted VTOL UAV in which he designed a new model and analyzed using CFD packages. In this project, CFD plays an important role in predicting the longitudinal and lateral stability and control characteristics of a full-scale model of ducted fan VTOL UAV at both vertical and horizontal flight without any prior knowledge of existing wind tunnel or flight test data.

III. BASELINE GEOMETRY SELECTION

The baseline BWB geometry is defined in Ref. [1] for the MOB project, which is based on a previous BWB design as described in Ref. [13]. The half-model geometry is composed of the central body, an inner wing and an outer wing to which a winglet is attached. They are ''blended'' to form the BWB geometry. The total span including the winglets is just less than 80 m. For the present study, the propulsion system and its integration with the BWB design is not included, although its importance is fully appreciated. The design conditions considered correspond to the first segment of cruise as specified in Ref. [13]. Hence, to balance the weight of the aircraft, the design C_L is 0.41[2] based on the reference area of 842 m^2.

This geometry outline is scaled down about 40 times to incorporate the design features of a small UAV. The wing span is kept constant to 1 meter. The root chord is 520 mm. Therefore the aspect ratio has changed little. The average sweep back angle also has some small variation about 1 degree. The scaled model is geometrically as well as dynamically similar.

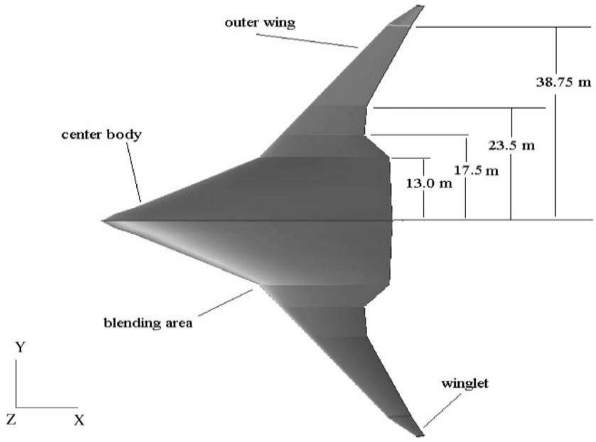
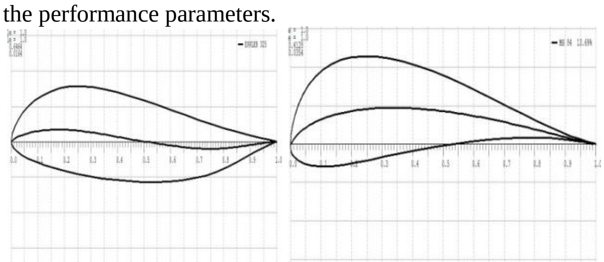


Fig. 1 Outline dimensions of CAD model from Ref.1

IV. PRIMARY ANALYSIS OF BASELINE DESIGN AND ITS OPTIMIZATION

The preliminary analysis for the scaled baseline model is done in XFLR5. The airfoils with low Reynolds number are selected for the geometry. Since the Blended wing Body is similar to a flying wing concept and as it is not having a tail section to control the pitching moment, the wing itself should control the moments. Therefore the trailing edge should produce a lift downward to balance the moment. Such airfoils having a different trailing edge are called as 'reflected camber' airfoils or 'reflex camber' airfoils. Five airfoils are selected for analysis in which two of them are shown in Fig.2. All these airfoils have been analyzed on the basis of Reynolds number, starting from 10000 to 500000 with an increment of 10000. The Batch analysis and the Multi-thread analysis tools analyze each airfoil for minimal errors and calculate the performance parameters.



(a) (b)

Fig. 2 Airfoils (a) EPPELER 325 (b) MH-84

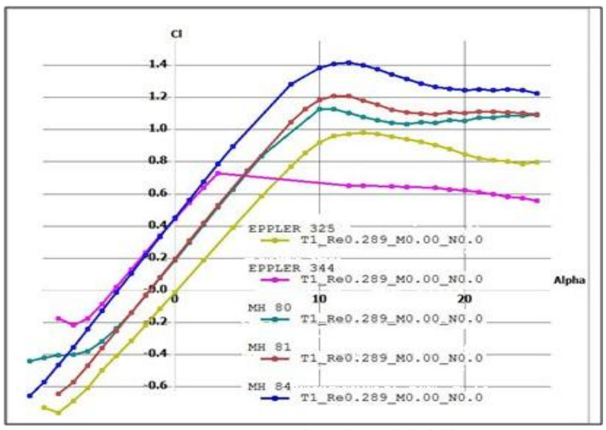


Fig. 3 c_l vs. α for selected airfoils

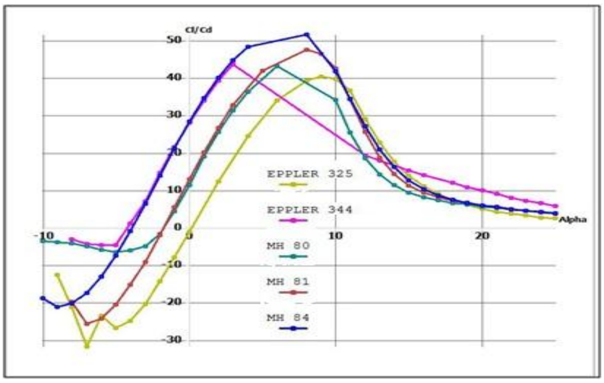


Fig. 4 c_l / c_d vs. α for selected airfoils

The airfoil named MH-84 is chosen among the five analyzed airfoils. As there is a need to increase the thickness to accommodate the internal equipments as well as the ducted fan (in further updated design), the thickness of MH 84 is increased from 13.72% to 19.97% of the chord. The position of maximum thickness and the camber is kept unchanged. The new airfoil is named as MH 84 20%. This airfoil is used for the baseline design and for the further optimized designs.

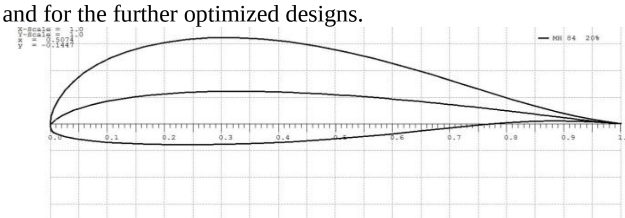


Fig. 5 Optimized airfoil MH 84 20%

The new airfoil is used design the 3D model in XFLR5 and to analyze it.

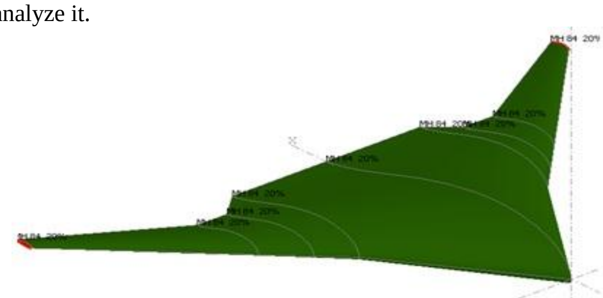


Fig. 6 3D model from XFLR5

The 3D panel method is chosen for the wing analysis. The lifting line theory (LLT) as well as the Vortex Lattice Method (VLM) is also preferable. For the flying wing configuration the 3D panel Method is more preferred. The mode is considered to be viscous. The preset for the polar is set to be fixed speed. The plots will be c_l against AOA. The values for density and kinematic viscosity have been chosen from standard atmosphere for the cruise condition.

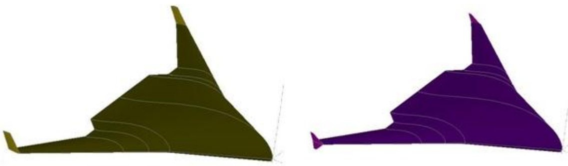


Fig. 7 Models with different types of winglets

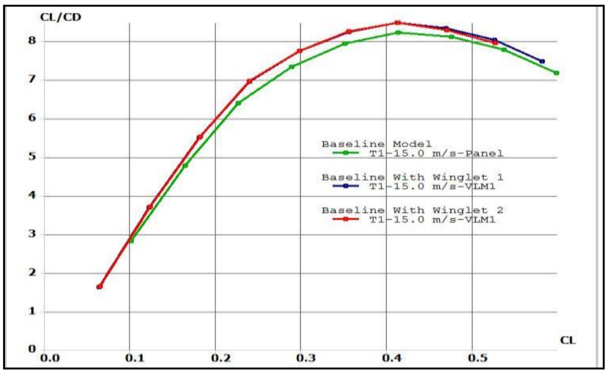


Fig. 8 L/D comparison for baseline and winglet models

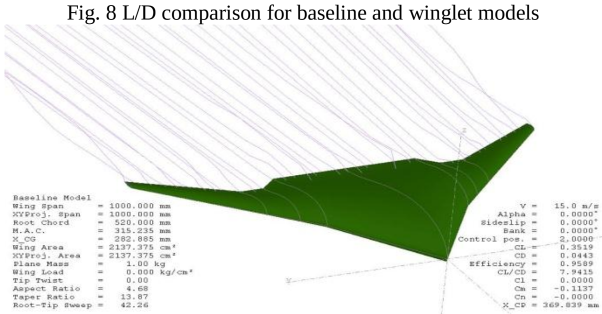


Fig. 9 Disturbed velocity streamlines for baseline design

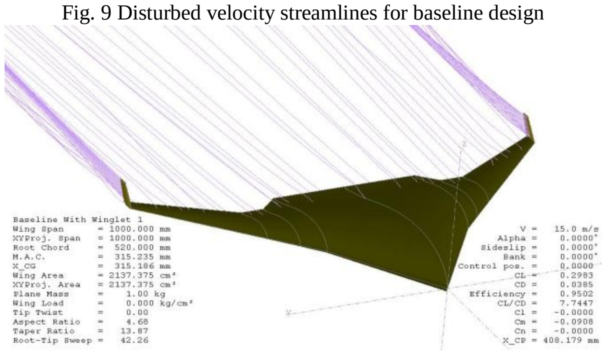


Fig. 10 Smooth velocity streamlines for winglet design

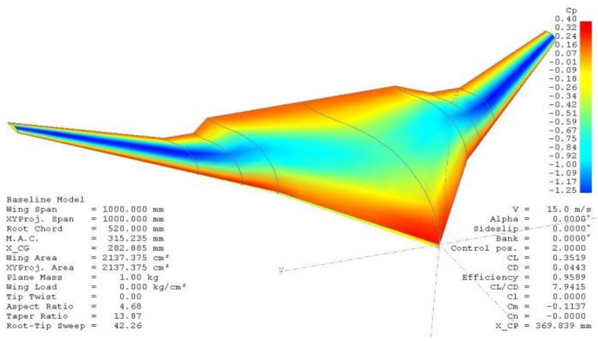


Fig. 11 Cp distribution over baseline model

A. *Optimization of the Baseline Model*

The results of preliminary analysis for the baseline design are just satisfying for the design condition. The body is able to generate sufficient lift in its cruise condition. But considering the conversion of this baseline design to ducted fan configuration, there will be loss of planform area. Two ducted fans of diameter 76mm are placed vertically in either sides of the wing. This creates reduction in lift produced by wing and increase the total drag.

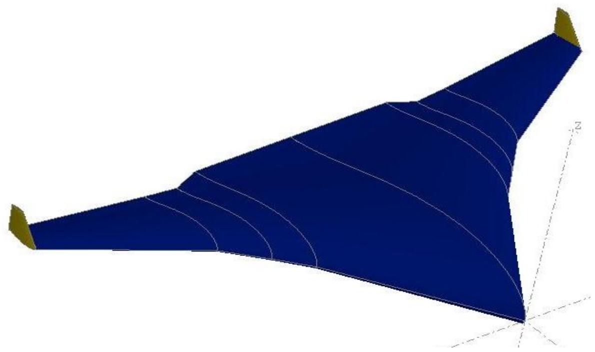


Fig. 12 Optimized model

This leads to the need of an optimized design which can fly at a fixed speed of 15m/s as well as able to lift the body with ducted fan configuration. The conventional methods of optimization was done in which many number of trials were done. This included in changing tip chord lengths, sweep angles etc. The optimized model is shown in Fig.12.

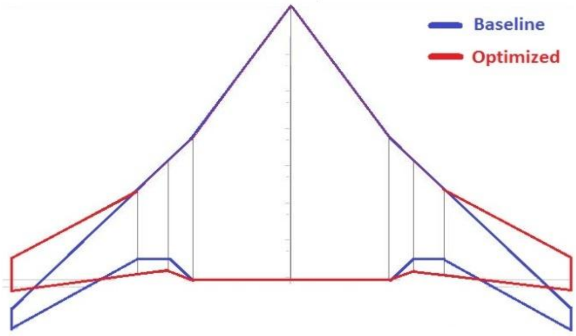


Fig.13 Shape comparison of baseline and optimized models

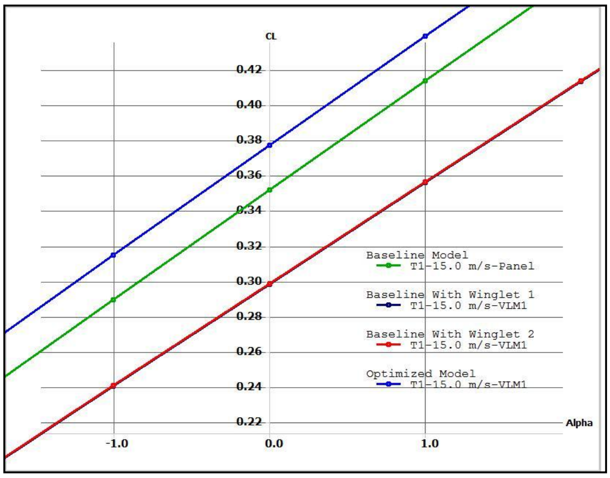


Fig.14 c_l vs. α for various models

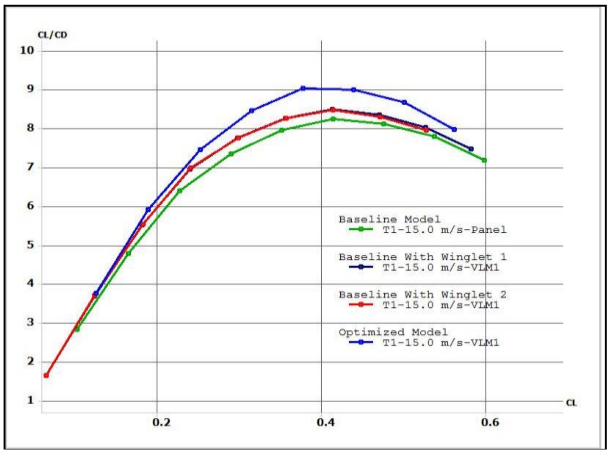


Fig.15 L/D comparison for various models

From the graphs shown in Fig.14 and Fig.15, it is clear that the optimized design has a better performance over the baseline design. The C_{Lo} has increased to 0.381 where the required value for optimized design calculation was 0.344. The L/D ratio also has increased to about 9 which confirm the increment in lift.

V. MODELING AND THREE DIMENSIONAL CFD ANALYSIS FOR NORMAL AND DUCTED FAN CONFIGURATION

A. Optimization of the Baseline Model

The preliminary analysis of BWB UAV gave a good view about the aerodynamic parameters for its cruise flying condition. The limitations of XFLR5 in computing the results for the body at higher angle of attacks are obvious. This can be compensated by the CFD analysis of CAD model in ANSYS CFX. In this chapter the CAD modeling is done in CATIA V5. It is exported to ICEM-CFD for its fine surface meshing. The output file is imported in CFX-Pre for initializing the input conditions. After specifying the Boundary conditions and the domain parameters, the body is analyzed in CFX-Solver. The result file is processed in the CFX-POST post processor.

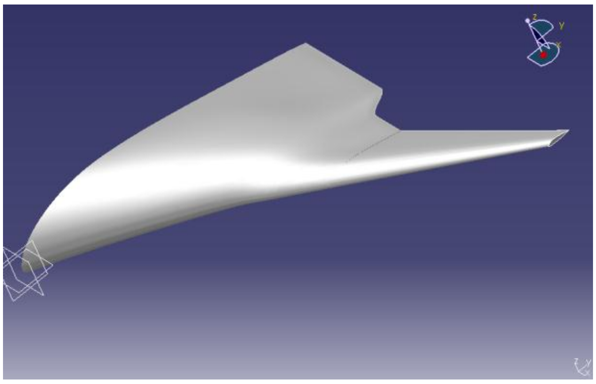


Fig.16 3D model developed in CATIA

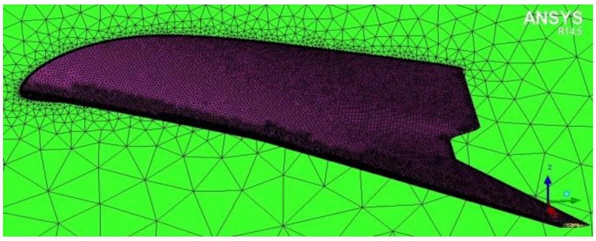


Fig.17 Model meshed in ICEM-CFD

For the volume mesh, 'Tetrahedral' elements are selected. Robust method is used for the meshing. After the normal meshing the possible errors are checked using the 'Check Mesh' option. The quality is checked and further smoothing is done. Prism mesh is created for the body for capturing the boundary layer properties.
Boundary conditions specify the flow and the thermal variables on the boundaries of physical model. They are, therefore, critical components of CFD simulations and it is important that they are specified appropriately. The boundary conditions are set in the CFX-Pre.

A new user defined material is created named 'CRUIZE' which has the properties exactly similar as that of the cruise condition. The height is considered about 1000 m above the sea level.

TABLE.1 BOUNDARY CONDITIONS FOR ANALYSIS

Boundary	Properties	
Inlet	Flow Regime	Subsonic
	Normal Speed	15 m/s
	Turbulence Intensity	5%
Outlet	Flow Regime	Subsonic
	Relative Pressure	0 Pa
Walls	Type	Free Slip Wall
Wings	Type	No Slip Wall
	Wall Roughness	Smooth Wall

The optimized design is converted to ducted fan configuration for acquiring the VTOL properties. The objectives of this conversion include decreasing the difficulties of hand launch, runway requirements etc. The properties and specifications of the selected ducted fan are described below.

TABLE.2 SPECIFICATIONS OF DUCTED FAN

EDF Ducted Fan - 76 mm	
Blade Diameter	74 mm
Duct Diameter	76 mm
No. of Blades	5
Blade Twist Angle	450
Power	300~1000g Thrust
Recommended Motor	24-33 8Turn (7.4~11.1v)
Shaft Diameter	3 mm
ESC	20A
RPM	4500 kv
Motor	Up to 24 mm

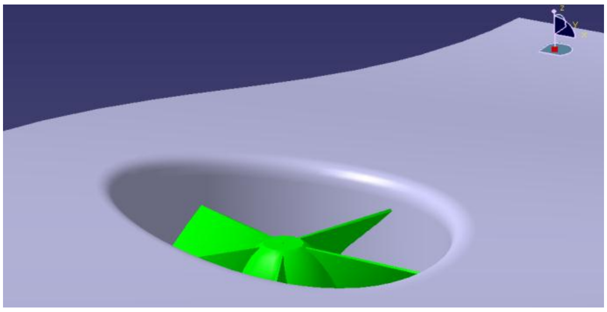


Fig.18 Ducted fan configuration for optimized model

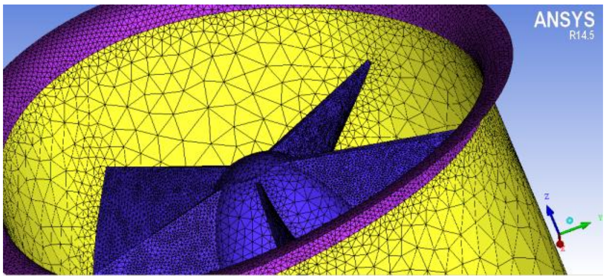


Fig.19 Tetrahedral Mesh for fan and duct

The analysis for this ducted fan configuration is done with a special rotating domain which was created in the duct. The upper and lower walls of duct together with the cylindrical surface form the rotating domain. The rest of the domain region remains stationary.

VI. RESULTS AND DISCUSSIONS

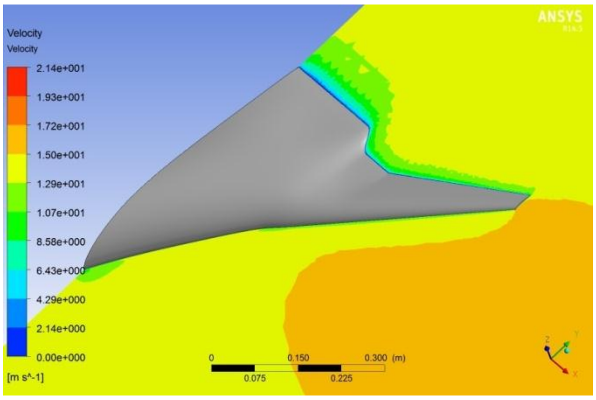


Fig.20 Velocity contours over the mid plane

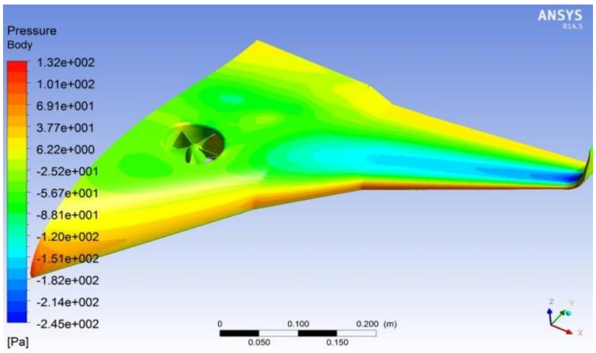


Fig.21 Pressure distribution over the Ducted Fan model

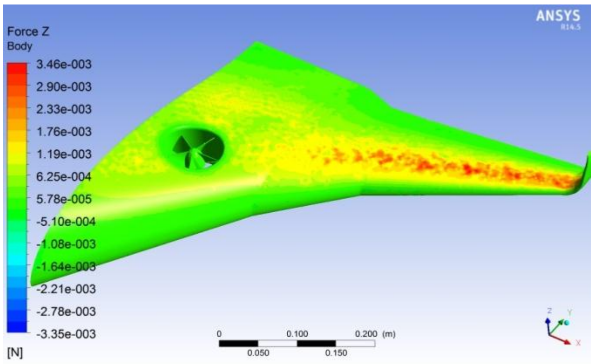


Fig.22 Lift force distribution over the Ducted Fan model

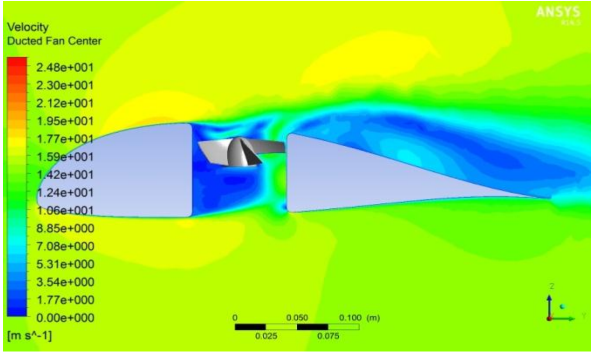


Fig.23 Velocity contours at the center of the duct

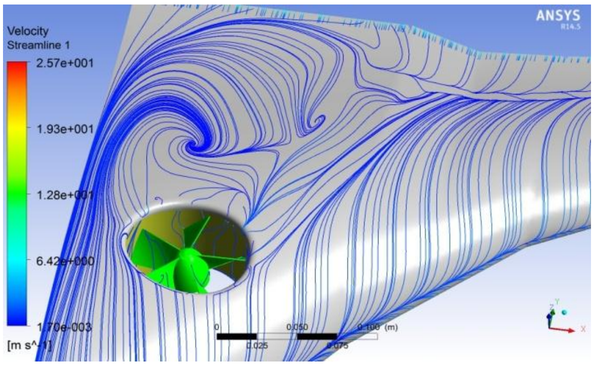


Fig.24 Surface streamlines over the body

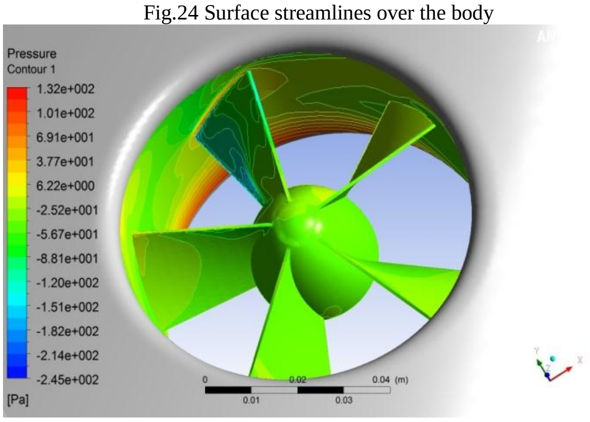


Fig.25 Pressure distribution over the duct and fan

TABLE.3 RESULTS VALIDATION WITH LITERATURE

Parameters (at 0^0 AOA Cruise Condition)	XFLR 5	ANSYS
C_{L0}	0.377	0.371
C_{D0}	0.0425	0.0421
L/D	8.85	8.81

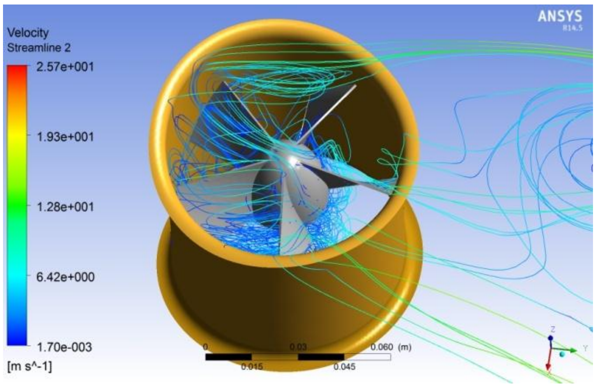


Fig.26 3D streamlines generating from duct

The results of both XFLR5 and ANSYS are compared in Table 3. The limitations of XFLR5 are compensated in the CFD analysis in ANSYS and the results are more accurate. From Fig.24 it is clear that the flow is getting disturbed at the backward portion of duct. The turbulence is more in that region due to the rotation of the fan. The optimized design is capable of lifting the total weight in the midst of all these losses.
The loss of planform area was about 5% for the optimized design. Still the modifications were fruitful to produce the sufficient lift over the wing surface.

VII. CONCLUSIONS

The Blended Wing Body (BWB) UAV is analyzed using CFD for the study of its aerodynamic characteristics. The optimized design is having better results over the baseline design. The 3D model is analyzed at a fixed speed of 15 m/s which is at a low Reynolds number.
Analysis for the ducted fan configuration is done with the combination of stationary as well as rotating domain. The interaction of streamlines with fan is visualized and various contours of pressure, velocity, force, shear stress etc. are plotted.

All the graphs generated from XFLR5 and results from ANSYS are compared and validated with the existing literature. The Ducted fan configuration was a bit unsuccessful only in the longitudinal stability which can be solved by adjusting the CG locations.

The results from the present work are compared with those from the existing literature [2]. The models are dynamically similar and the speed ranges are in subsonic incompressible zone.

The future scope of this work includes stability analysis, the dynamic analysis, design of control surfaces for its lateral and longitudinal controls etc.

REFERENCES

[1] N. Qin and A Vavalle. '*Aerodynamic considerations of blended wing body Aircraft'* Progress in Aerospace Sciences 40 (2004) 321–343

[2] Wirachman Wisnoe, Rizal Effendy Mohd Nasir. *'Wind Tunnel Experiments and CFD Analysis of Blended Wing Body (BWB) Unmanned Aerial Vehicle (UAV) at Mach 0.1 and Mach 0.3'* 13th International Conference on *AEROSPACE SCIENCES & AVIATION TECHNOLOGY, ASAT- 13, May 26 – 28, 2009.*

[3] Toshihiro Ikeda. *'Aerodynamic Analysis of a Blended-Wing-Body Aircraft Configuration'* School of Aerospace, Mechanical and Manufacturing Engineering, Science, Engineering and Technology Portfolio, RMIT University, March 2006

[4] LI Peifenga and ZHANG Binqian *'Aerodynamic Design Methodology for Blended Wing Body* Transport', Chinese journal of aeronautics, Shanghai Aircraft Design and Research Institute, Commercial Aircraft Corporation of China□Ltd. , Shanghai 200232, China

[5] M. Zhang and A. Rizzi, *'Aerodynamic Design Considerations and Shape Optimization of Flying Wings in Transonic Flight'* '12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM 17 - 19 September 2012, Indianapolis, Indiana

[6] Nimeesha B. Kuntawala ' *Aerodynamic Shape Optimization of a Blended-Wing-Body Aircraft Configuration*' Masters of Applied Science Graduate Department of Aerospace Engineering University of Toronto 2011

[7] Cengiz Camci and Ali Akturk, ' *A Computational and Experimental Analysis of a Ducted Fan used in VTOL UAV Systems*' Turbo-machinery Aero-Heat Transfer Laboratory- Department Aerospace Engineering, Pennsylvania State University, University Park, PA 16802

[8] Ali Akturk and Cengiz Camci, ' *Double Ducted Fan (DDF)*' Turbo-machinery Aero-Heat Transfer Laboratory- Department Aerospace Engineering, Pennsylvania State University, University Park, PA 16802

[9] Osgar John Ohanian III, ' *Ducted Fan Aerodynamics and Modeling, with Applications of Steady and Synthetic Jet Flow Control'*, Virginia Polytechnic Institute and State, Blacksburg, VA 2011

[10] Hui Wen Zhao, ' *Development of a Dynamic Model of a Ducted Fan VTOL UAV*', School of Aerospace, Mechanical and Manufacturing Engineering College of Science, Engineering and Health RMIT University August 2009.

[11] Bolsunovsky AL, Buzoverya NP, Gurevich BI, Denisov VE, Dunaevsky AI, Shkadov LM, Sonin OV, Udzhuhu AJ, Zhurihin JP. *Flying wing—problems and decisions*. Aircraft Des 2001;4:193–219

[12] Liebeck RH. *Design of the blended wing body subsonic transport*. J Aircraft 2004; 41(1)–25.

[13] Smith H. '*Blended wing body development programme*' College of Aeronautics Proceedings of 22nd International Congress of Aeronautical Sciences, Paper 1.1.4,2000

[14] Portsdam MA, Page MA, Liebeck RH. *Blended wing body analysis and design*, AIAA Paper 1997-2317, 1997

[15] Laban M, Arendsen P, Rouwhorst WFJA, Vankan WJ. *A computational design engine for multi-disciplinary optimization with application to a blended wing body configuration* AIAA Paper 2002-5446

[16] Wakayama S. *Blended-wing-body optimization problem setup* AIAA Paper 2000-4740, 2000.

[17] Carlsson M, Kuttenkeuler J. *Design and testing of a blended wing body aeroelastic wind tunnel model*. J Aircraft 2003; 40(1):211–3.

[18] Green JE. *"Greener by design-the technology challenge*". Aeronaut J 2002;106(1056):57–113

[19] Roman D, Gilmore R, Wakayama S. *Aerodynamics of high subsonic blended-wing-body configurations,* AIAA Paper 2003-0554, 2003.

[20] Bartholomew P, Lockett H, Gallop J. *The development of the MOB data and product management system* AIAA 2002-5450, 2002

[21] Data from Internet Sources.