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Quantification of Aerodynamic Variables Using Analytical Technique and Computational Fluid Dynamics

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***Abstract*—**Aerodynamic stability coefficients are necessary to be known before any unmanned aircraft flight is performed. This requires expertise on aerodynamics and stability control of the aircraft. To enable efficacious performance of aircraft requires that a well-defined flight path and aerodynamics should be defined beforehand. This paper presents a study on the aerodynamics of an unmanned aero vehicle (UAV) during flight conditions. Current research holds comparative studies of different parameters for flight aerodynamic, measured using two different open source analytical software programs. These software packages are DATCOM and XLRF5, which help in depicting the flight aerodynamic variables. Computational fluid dynamics (CFD) was also used to perform aerodynamic analysis for which Star CCM+ was used. Output trends of the study demonstrate high accuracies between the two software programs with that of CFD. It can be seen that the Coefficient of Lift (CL) obtained from DATCOM and XFLR is similar to CL of CFD simulation. In the similar manner, other potential aerodynamic stability parameters obtained from analytical software are in good agreement with CFD.

***Keywords*—**XFLR5, DATCOM, computational fluid dynamic, unmanned aero vehicle.

I. Introduction

In the past few years, there have been significant researches and development has made progress in the technology of UAVs. System identification is very necessary for the complete description of any system dynamics that is explained by the help of mathematical models based on the different inputs and outputs for the system under observation. In order to quantify the response, excitations on the control surfaces, must be simulated to a take-off aircraft model from its equilibrium state [1], [2]. In this way, it is easy to obtain more accurate results or aerodynamic derivatives prediction as compared to CFD or wind tunnel test [3].

The quantification of aerodynamic variables is pains taking job; however, to achieve this, there are several different techniques. These techniques are a) CFD, b) DATCOM, c) XFLR5, d) AeroVASP, e) Wind Tunnel, f) flight data and etc. From these mentioned ways wind tunnel and CFD are time consuming and costlier techniques, however, DATCOM, XFLR5 and AeroVASP are analytical techniques of measuring the aerodynamics variables.

In any UAV, a mechanically controlled aileron, elevator and rudder has a higher development risk due to uncertainties in the aerodynamic behavior over the control surfaces. Common problems for aerodynamically balanced UAV are high coefficient of moment at high speed and a tendency to over balance in sideslips motion. To increase the knowledge and reduce the future development risk, in this research, a model of a UAV is implemented in the CFD, DATCOM and XFLR; moreover, this model is kept constant in all three simulation platforms.

When UAVs are considered, there is a slot between the moving control surface and fixed points of the airfoil. Flow characteristics are defined by a ratio of inertial resistance to viscous resistance for a flowing fluid (i.e. Reynolds number) and the ratio between the speed of a body and speed of sound in the surrounding medium, which is a Mach number. This makes it a necessary task to have a geometry model of UAV that gives the acceptable controlling over the control surfaces in the entire speed regime. Achieving the right Mach and Reynolds numbers is difficult in wind tunnel tests; however, it would require a pressurized tunnel. Nevertheless, tunnel walls also induce variation in up-wash on the spanwise location of the wing, which causes the normal downwash to decrease [4], [5]. Thus, analyzing a wing or lifting body under wind tunnel will induce little downwash; moreover, this happens when the wing seems to have a larger effective aspect ratio than the tested version in free air. However, wings with smaller span than the wind tunnel actual width experience less distortion of such types. In addition to this, lift distribution generated by large-span models when tested in a wind tunnel, causes high distortions, that induces variability in stalling characteristics [6]. To remove such interference, a correction factor is used. However, the accuracies and implementation are not always worthwhile, especially when the prototype is mounted on the wind tunnel's floor and the boundary layer detachment may also be affected by such an arrangement. Nevertheless, flight tests give the right conditions however they are costly and conceivable just at a late phase of a design project. That is why in this research, analytical approach is discussed and implemented. Justification of results is obtained from analytical software that are DATCOM and XFLR; furthermore, CFD is used to validate the analytical results. In this research CFD simulations were conducted on Star CCM+.

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DATCOM is an open source software generated by the United State Air Force (USAF). This program executes the strategies contained in the USAF stability, and control to ascertain the static stability, control and dynamic derivative characteristics of fixed-wing aircraft. Computerized DATCOM requires the input of data records containing a geometric depiction of an aircraft, and yields its comparing dimensionless stability derivatives as indicated by the predetermined flight conditions. These values can then be utilized to compute significant characteristics of flight dynamics. XFLR5 is also an open source software that is used for the design and analysis of airfoils that are operated at low Reynolds number. It calculates characteristics such as the drag and pressure distributions. CFD is a technique that uses Navier Stokes Equations (NSE) to solve flow regime over a certain object. Moreover, it is not only dependent on NSE's, it also implements some more equation models to ascertain that boundary layer attachment and wake is well defined. Therefore, by carrying out this study, researchers related with aerospace application will have an open window over how they can benefit themselves by using open source analytical software in line with CFD. Moreover, the steps required to be taken for using different schemes of analysis have been elaborated in a schematic layout, as shown in Fig. 1. The figure describes the different steps needed to be performed for determining the aerodynamic parameters using DATCOM, XFLR and CFD. However, CFD steps have been taken from an earlier publication of determining flow over cambered aerofoil for wind turbine analysis, which was published by the author [7].

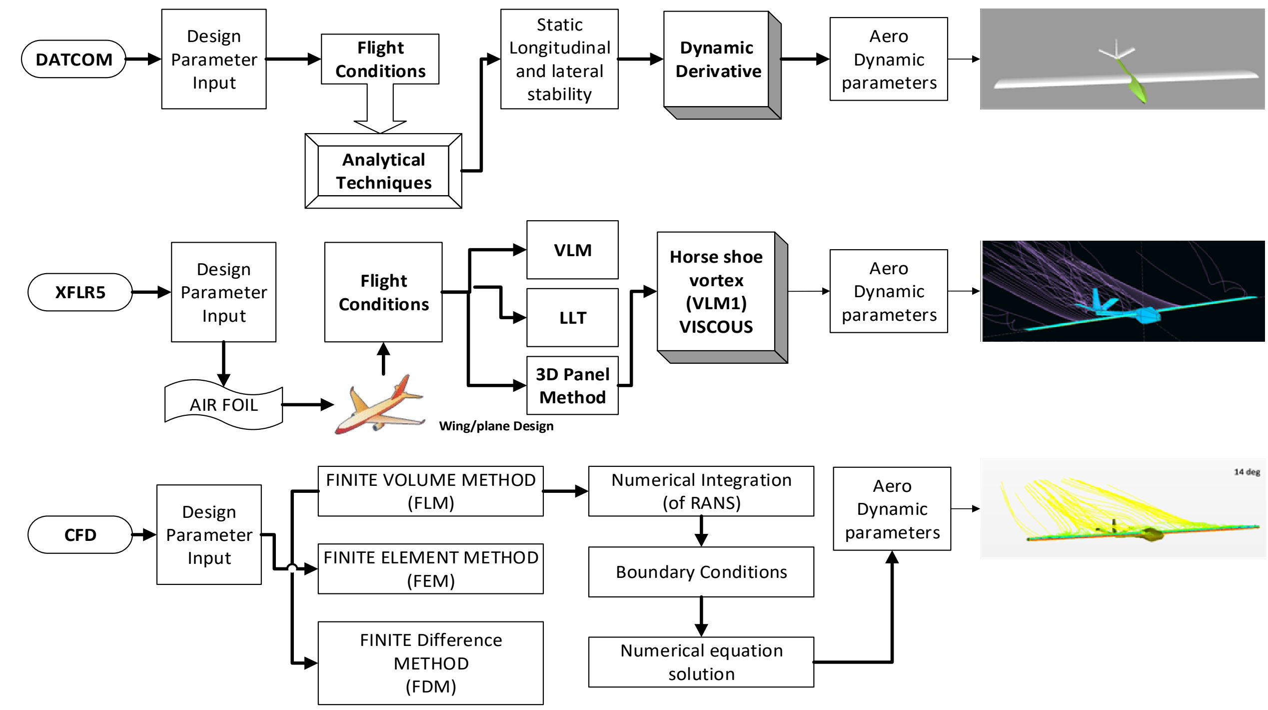

Fig. 1 Schematic layout of the techniques used for processing aerodynamic variables i.e. top is DATCOM, middle is XFLR and last is the CFD process.

II. Methodology

Basic equations that are used for calculating aerodynamic coefficients in all the three methods are similar. However, CFD is a more proficient way of calculating these variables as the flow is considered over each and every single corner, and moreover, air viscosity and shear stress due to near wall condition is also considered, but in numerical methods they are undermined. Equations used for analyzing different coefficients, whose graphs are presented in the results section, are described below for readers and researchers help. Five major variables were calculated from DATCOM, XFLR5 and CFD. The conditions were set at 1000 meters above sea level. Density was set at 1.126 kg/m^3. Kinematic viscosity was set as 1.581x10-5. Wingspan and other details of the aircraft are provided in Table I. Five major variables of aerodynamics dimensionless coefficient have been calculated using different techniques. These variables are **C_L**, Coefficient of Drag **(C_D)**, Coefficient of Pitching moment **(C_m)**, Coefficient of Rolling moment **($C_{l\text{-}roll}$)** and Coefficient of Yawing moment **(Cn).**

C_L – Lift Force Coefficient

C_L is the dimensionless coefficient of lift, this is the force coefficient which is used for measuring the lift forces acting on the aircraft; this is in the Z direction. This force acts in an opposite direction to weight of the aircraft, as this force helps the aircraft to fly. The lift force is described in (1), where Z is Lift force, $\bar{q}$ is dynamic pressure and S is area.

$$Z = C_L \bar{q} S c \tag{1}$$

where the coefficient of Lift force functionalities are defined using (2);

$$C_L = f(\alpha, \delta_E, i_H) \quad (2)$$

where α is the angle of attack, δ_E is elevator deflection angle, and i_H is related with the stabilator deflection angle.

TABLE I
GEOMETRICAL ASPECTS OF AN UAV

Wing design	
Span	1.3 m
Area	0.23 m
Mean aerodynamic chord	0.18 m
Aerofoil used	NACA 3412
Inertial parameters	
Ixx	0.2897 kg.m^2
Iyy	1.054 kg.m^2
Izz	1.355 kg.m^2
Ixz	-0.04081 kg.m^2
Fuselage	
Maximum length	0.95 m
Maximum Take-off weight	12 Kg
Horizontal Tail	
Span	0.12 m
Root chord	0.14 m
Tip chord	0.14 m
Sweep	18.43 deg
Dihedral	25 deg
Aerofoil used	NACA 0012
Vertical Tail	
Span	0.12 m
Root chord	0.14 m
Tip chord	0.06 m
Sweep	9.46 deg
Aerofoil used	NACA 0012
Aerodynamic atmospheric properties	
Gravity	9.8 m/s^2
Velocity	35 m/s

C_D – Drag Force coefficient

C_D is the dimensionless coefficient of drag; this is the force coefficient which measures the drag forces against the flow of aircraft. This is an important factor for determining the aerodynamic smoothness of the body when it flows against the airflow. The drag force is described in (3), where D is Drag force, $\bar{q}$ is dynamic pressure and S is area.

$$D = C_D\bar{q}Sc \quad (3)$$

where the coefficient of Drag force, functionalities are defined using (4);

$$C_D = f(\alpha, \delta_E, i_H) \quad (4)$$

where α is the angle of attack, δ_E is elevator deflection angle, and i_H is related with stabilitor deflection angle.

C_m – Pitching Moment coefficient

C_m is the dimensionless coefficient of pitching moment; this is a moment coefficient that tells about the pitching moment of the aircraft about its center of gravity (CoG) location. C_m is important for determining the aircraft stability about its CoG position. The pitching moment is described in (5), where M_A is Pitching moment, $\bar{q}$ is dynamic pressure and S is area.

$$M_A = C_m\bar{q}Sc \quad (5)$$

where the coefficient of pitching moment functionalities are defined using (6).

$$C_m = f(\alpha, \delta_E, i_H) \quad (6)$$

Where α is the angle of attack, δ_E is elevator deflection angle, and i_H is related with stabilitor deflection angle.

$C_{l\text{-roll}}$ – Rolling Moment coefficient

$C_{l\text{-roll}}$ is the dimensionless coefficient of rolling moment about the X-Axis (i.e. it is related with the axis against the flow of air). The rolling moment is described in (7), where L_A is Rolling moment, $\bar{q}$ is dynamic pressure, S is area and b is the span of UAV.

$$L_A = C_{l-roll}\bar{q}Sb \quad (7)$$

where the coefficient of rolling moment functionalities are defined using (8).

$$C_{l-roll} = f(\beta, \delta_A, \delta_R) \quad (8)$$

where β is sideslip angle, $\delta_A$is aileron deflection angle, and δ_R is rudder deflection angle.

Cn – Yawing Moment coefficient

Cn is the dimensionless coefficient of yawing moment created by rudder deflection and it creates yawing effect on the aircraft. The yawing moment is described in (9), N_A is Yawing moment, $\bar{q}$ is dynamic pressure, S is area and b is the span of UAV.

$$N_A = C_n\bar{q}Sb \quad (9)$$

where the coefficient of yawing moment functionalities are defined using (10).

$$C_n = f(\beta, \delta_A, \delta_R) \quad (10)$$

where β is sideslip angle, $\delta_A$is aileron deflection angle, and δ_R is rudder deflection angle.

These are parametric formulas utilized for calculating aerodynamic conditions of the UAV.

A. Designing of UAV

UAV was designed using XFLR5 plane designing module. Before designing the UAV, its aerofoil for wings, the vertical stabilizer and horizontal stabilizer were designed using a module named Xfoil direct-foil design which is a part of XFLR5. The ingenuity behind this software is that it helps in designing and then analyzing the properties and physical aspects of the desired geometrical shape. This helps in saving ample amount of time for relocating the file from one software to another. XFLR5 initially helps in determining the aerofoil aerodynamic properties. Moreover, these properties are then used within another XFLR5 module i.e. plane design for plugging the aerofoil section to the wing and other aerodynamic lifting devices.

B. XFLR Analysis of Aerodynamic Variables

XFLR5 Plane designing module allows to easily design as well as visualize the input variables while changing different design parameters of the aircraft body. The geometrical shape parameters table is jotted in Table I.

After designing the aircraft, aerodynamic analysis of complete aircraft was carried out for measuring different coefficients of stability. Vortex lattice method was used, within the analysis setting X-CofG was set at 0.09 m and Z-CofG was set at 0.003m, moreover, velocity was used as 35 m/s. Physical attributes were set as density equal to 1.112 kg/m^3 and viscosity was equal to 1.581x10-5 m^2/s. Dirichlet boundary conditions were set for analysis.

C. DATCOM Analysis of Aerodynamic Variables

In addition, to validate the parameters achieved from the XFLR5, later DATCOM, the most commonly used software for the analysis of aerodynamic control and stability, was used. However, in DATCOM, the design cannot be directly imported; it was required to set the designing parameters before carrying out the analysis. Setting the parameters within DATCOM requires understanding and measurement of the parameters from the center of gravity point. These parameters are used for initially describing the aircraft geometrical datum and reference point from where whole body i.e. fuselage, wing and tails will be designed. Once this task is carried out, then the fuselage parameters are given to the input script. Now, the wing design parameters are submitted with an aerofoil name by which DATCOM generates a wing of the given specification. Wing designing can be further modified by adding control surfaces over it i.e. designing ailerons and flaps. Finally, tail designing is carried out, in which horizontal and vertical tails are designed. Last, but not least, control surfaces can also be designed over the horizontal and vertical stabilizers for control analysis. However, in the current paper, control stability is not our major concern. This paper holds importance for aircraft aerodynamicist as this comparison provides the reader and researcher to avoid wasting time, material cost and purchasing expensive high-end CFD software, it is better to approach using open source software for predicting aerodynamic variables. Nevertheless, this paper holds a strong validation between two software programs i.e. between XFLR5 and DATCOM. UAV and aircraft designing using these software programs can be of big help, since the predictability of trends between the two is really high. The geometry designed over XFLR5 was in 90-95% agreement with the design depicted by the DATCOM by variable input. This can further be seen using Figs. 2 and 3.

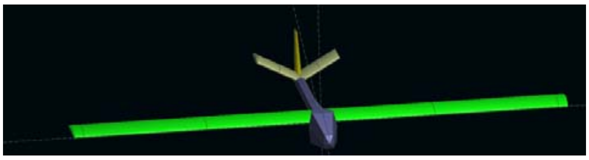

Fig. 2 Visualization from XFLR 5

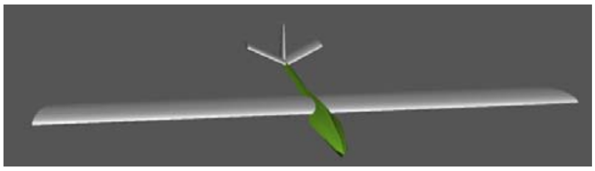

Fig. 3 AC3D output generated from DATCOM geometric data

D. CFD Analysis

CFD was carried out using Star CCM+, the model was imported in a .stl format. Meshing was carried out by setting the base size of about 0.12 m. Furthermore, the base of geometry size was set to 20% of the base size. The prism layer was defined as 8 for the boundary layer attachment over the body. Surface wrapper was also used for wrapping unwanted open surfaces on the model geometry, for which the wrapping scale was set at 15%. Polyhedral mesher was used for meshing the model. For physics conditions, Reynolds Average Navier Stokes (RANS) model with K-Epsilon turbulence modeling was used.

III. Results and Discussion

After achieving different results of aerodynamic variables from two different software programs, they were plotted against angle of attack to know the response and similarity of their trends. Moreover, results of CFD were also superimposed in the similar figures to get an idea of their fluctuations and trend fashion to the analytical results. These results are presented in this section in detail.

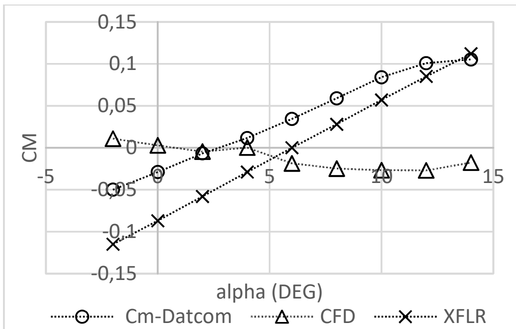

Fig. 4 Comparison between coefficient of pitching moment from CFD, XFLR and DATCOM

The results obtained from XFLR and DATCOM demonstrates high similarities between the trends of the coefficient of moment (CM) as shown in Fig. 4. The results obtained from XFLR for CM is starting approximately from -0.1; however, CM achieved from DATCOM is slightly higher at similar alpha i.e. 0 degrees. However, results obtained for the pitching moment coefficient from CFD is varying in an undermined fashion. Nonlinear trend of the CM obtained from CFD can be explained by irregularities generated by vortices, this ambiguity is also observed and explained by Bai-Gang [1]. They explained that complex variation was observed in pitching moment with different angle of attack and giving arbitrary change to that of the experimental results. Furthermore, this nonlinear fashion in pitching moment was also depicted in several different studies [8]-[10].

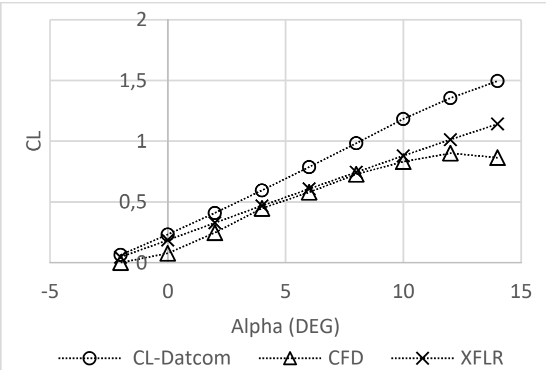

Fig. 5 Comparison between coefficient of lift from XFLR and DATCOM

The results obtained from XFLR and DATCOM demonstrate high similarities between the trends of coefficient of lift (CL), as shown in Fig. 5. The results obtained from XFLR for CL is starting approximately from similar point; however, as the angle of attack is increased there is a slight variation in DATCOM results. Moreover, the results from CFD is highly coinciding with the results of XFLR, demonstrating good agreement between the two.

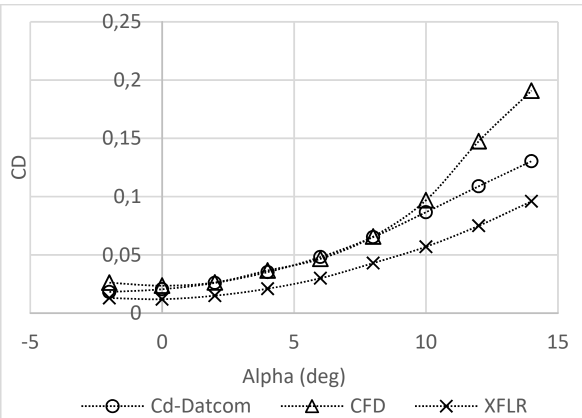

Fig. 6. Comparison between coefficient of drag from XFLR and DATCOM

From Fig. 6, the coefficient of drag demonstrates similar trends between the outputs of XFLR and DATCOM to that of CFD. A slight variation can be seen for the CFD case as the angle of attack is increased above 10 degrees. Flow over the UAV demonstrates more boundary layer separation causing a slight increase in the coefficient of drag at higher values of alpha.

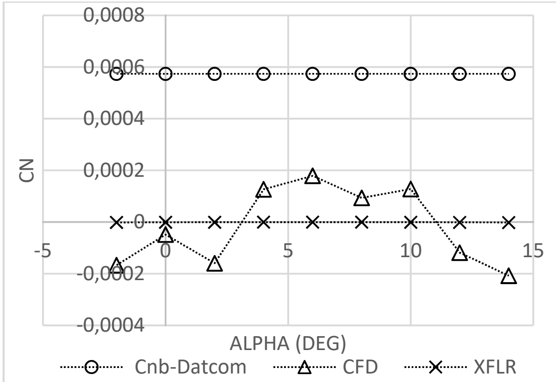

Fig. 7 Comparison between coefficient of yawing moment from XFLR and DATCOM

The results obtained from XFLR and DATCOM demonstrate similarity between the trends of coefficient of yawing moment (Cn), as shown in Fig. 7. The results obtained from XFLR for Cn is demonstrating varying trend with different angle of attacks however, in the case of DATCOM the results has a constant change from lower to higher alpha approximately at 5.74E-04; however, DATCOM achieved Cn is slightly lower at similar alpha, but, with variability. Moreover, the CFD result for Cn shows similar trend as compared to XFLR, however the DATCOM is slightly above in this case. The variation on different angle of attacks seems to be quite consistent. This is, as beta angle, was not considered during the simulation setup in all the three aspects.

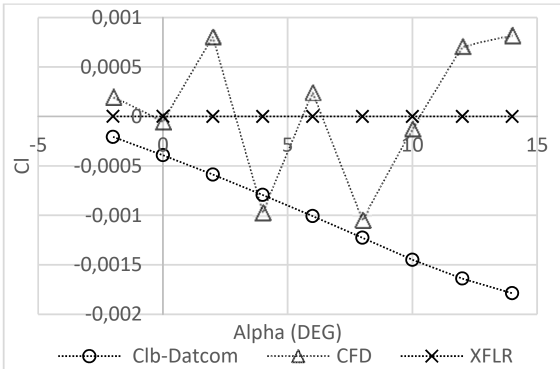

Fig. 8 Comparison between coefficient of rolling moment from XFLR and DATCOM

The results of coefficient of rolling moment (Cl) obtained from XFLR and DATCOM demonstrate similarity between the trends, as shown in Fig. 8. The results obtained from XFLR for Cl demonstrate decreasing trend with different angle of attacks, moreover, in the case of DATCOM, the results have a similar change as that of XFLR, but is on an upper notch. Moreover, the CFD results represented by triangular dotted line show a fluctuating trend. This fluctuation can be due to the meshing, as we change the angle of attack, it is obvious that the surface is re-meshed to acquire the new geometrical boundary conditions in consideration.

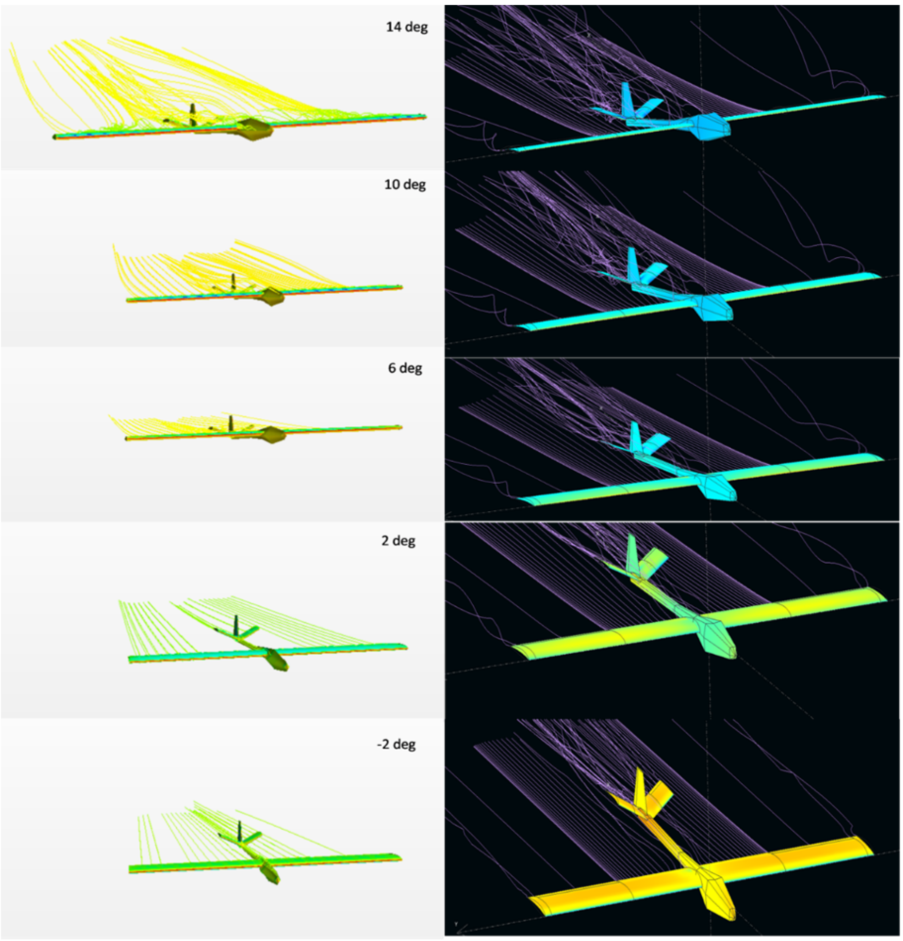

Fig. 9 Comparison between visualized streamlines over the surface of UAV; (a) Left hand designs generated by Star CCM+ and (b) Right hand designs generated by XFLR5

Fig. 9 represents the flow of air over the UAV. The demonstrative visualization was generated on Star CCM+ and XFLR5. The visual effects in Fig. 9 show high similarities between both software programs. However, the streamlines were limitedly chosen in Star CCM+ for computational time saving. Moreover, highly comparative results have been driven at both ends i.e. from Star CCM+ and XFLR5. However, from Fig. 8 it can be deduced that at lower angle of attacks, flows are quite similar in pattern; however, as the angle of attack is increased, the fluctuation of the aerodynamic variables is increased on CFD. This can be due to consideration of differential equations i.e. NSE in CFD, which are implemented with the turbulence modeling. In addition to this, CFD also computes the boundary layer detachment and attachment over the surface of UAV. The detailed analysis in CFD is further capable of analyzing shear stresses near the surface of the UAV. The wake is also considered in a more vivid manner in CFD simulation; however, the analytical results of the XFLR does depict similar patterns. Moreover, XFLR uses vortex lattice method and panel method by which wake is assumed as flat; however, with further approximations the wake tends to roll up; this phenomena is generated at the trailing edge of two wing tips [11].

Modeling wake using panel method has no significant effect on the coefficient of lift [11], but it does affect the induced drag value and its derived coefficients. Nevertheless, the flat wake does not take into account function of elevators in detail due to the downwash generated by the wings influences the flow field around the elevator. Similar illustration can be seen in Fig. 9, that Star CCM+ generated results have less wake intensity than that of the XFLR. The XFLR is slightly over predicting the wake generated behind the elevators causing more turbulence. Moreover, to measure wake, it is necessary to measure it in an iterative manner, in which the wake is relaxed on each iteration; this can be carried out using CFD. Furthermore, the wake meshing in XFLR5 is depicted using flat panel method, which reduces the accuracies of the results.

IV. CONCLUSION

The study holds a concurrent results and discussion on the topic of aerodynamics analysis of a UAV using analytical and CFD techniques. The depicted results of analytical solutions from DATCOM and XFLR5 trends are reasonably similar. However, the CFD coefficient of drag and coefficient of lift are also similar to that of analytical ones; nevertheless, CFD measured other aerodynamic variables are not significantly coinciding with the analytical solutions.

The results are still of extreme importance since they have depicted and illustrated that CFD and analytical solutions are capable enough to demonstrate similar trends with high accuracies; doing this helps in saving time and cost of running experiments.

In future, it can be proposed that after achieving the aerodynamic coefficients from these software programs can help in altering the design before final prototyping. Moreover, later aerodynamic coefficients can be used for predicting longitudinal and lateral stability derivatives for finding the transfer function and, by which, flight control models can be designed.

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