Analysis of a Tiltrotor Vertical Take-off and Landing Unmanned Aerial Vehicle: CFD Approach

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Abstract- In this current era of technology VTOL UAVS is an emerging technology that is becoming popular for its variety of applications like Agriculture, Civil, and military for Surveillance, rescue missions, and patrolling. These types of aircraft came into existence as the solution to many issues like lack of runways in rural areas and dense forests. VTOL UAV is a hybrid of a helicopter and fixed-wing aircraft because it has the functionality of both types of aircraft. These aircraft possess high hovering efficiencies like a helicopter and a better cruising speed like a fixed-wing aircraft with an enhanced payload capacity. Many interesting applications of these aircraft is attracting researchers to work in this field. In this paper, a CFD approach has been adopted for the analysis of TURAC tilt-rotor type VTOL UAV with the help of XFLR software.

1. Introduction

VTOL Technology has been under constant development over the centuries since Leonardo da Vinci’s manned VTOL designs through the World-War II era Rolls Royce’s Thrust Measuring Rig to the 21st century VTOL Unmanned Aerial Vehicles. [1]–[8]The development of UAV has increased exponentially over the years since the start of the 21st century which has led to the rapid development of V-TOL Technology owing to the operational difficulties arising due to the lack of landing abilities, lower flight ranges, and high energy demands. Initially, the Fixed-Wing UAVs[2] such as MQ1-Predator, Northrop Grumman RQ-4 were used for military operations in remote areas owing to their longer flight ranges, but with the evolution in the technology, the UAV technology has shifted to the VTOL domain due to the lower amount of runway needed to land and take-off the aerial vehicle, making them highly suitable for operations such as Attack, reconnaissance, delivery in remote areas as well as urban areas.[9] Generally, there are 6 types of Unmanned VTOL Aircraft being used commercially[10]–[13][11]: Tilting Ducted Fan(Propeller)[14], [15], Tilt Wing[16], Tilt Jet, Tiltrotor[12], Gyrodyne[17], and Thrust Vector Controlled VTOL[18], [19] as shown in Fig. 1 and 2.
Fig. 1 Tilted Ducted Fan (American Dynamics AD-150)[20], Tilt Wing (NASA G-10 “Greased Lightning”)[21], Tilt Jet (Bell-188A)[22], Gyrodyne (QH-50 Dash)[23], TVC VTOL (Lockheed Martin F-35 Lightning)[24]

Fig. 2 Classification of VTOL UAV

The Tilt Wing VTOL[12] utilizes the change in the orientation of the wing with fixed nacelles as a Takeoff and flight medium. Due, to the larger wing area susceptible to athwart winds, the Tilt Wing VTOL has lower hover efficiency. The Tilt Jet utilizes turning Jet engines to power the plane, imparting the plane longer flight ranges, higher speeds, and better stability, but at the same time, increasing the mass of VTOL and power demand, making them unsuitable for VTOL Applications. Gyrodyne[17] is a compound helicopter that uses a Vertical proppeller to facilitate the Take-off and landing of the plane and horizontal propellers for flight purposes, increasing the power demand, reduced speeds, and flight ranges. Thrust Vector controlled VTOL utilizes Thrust Vector control, motor speeds to orient the direction of engine thrust to control the speed
and altitude of the vehicle. Tilting Ducted Fan[9], [10] VTOL utilizes turning Ducted fans in cylindrical ducts, reducing the thrust losses on the propeller tips and increasing the lift on the plane, imparting the VTOL higher flight ranges, lower power demand, and higher velocities. The Tiltrotor [12][25] uses the orientation of the propellers fixed to rotors or nacelles to facilitate the flight of the VTOL by transitioning from Take-off to Flight over a change in propeller orientation. It reduces the power consumption of the VTOL while increasing the endurance time, Flight ranges, pitch stability, yaw stability, Plane speed, and payload capacity at low speeds and Reynolds number.

For their various advantages, the VTOL UAV has found multiple uses in the aviation industry. The VTOL UAV market has been estimated to grow by 19.73% in the period 2015-2020[26], due to an increase in the civilian and commercial applications of the VTOL UAV. The VTOL UAV is used for the following uses:

1. Surveying and Mapping[27]
2. Agricultural Monitoring [28]–[30]
3. Disaster Management[10]
4. Traffic Handling[31]
5. Wildlife and Forest Cover Monitoring[10]
6. Military uses[25]
Fig. 3 Examples of Commercial VTOL UAV (a) Wingtra One[32], (b) Autel Dragonfish[33], (c) HADA VTOL[34], (d) UKRSpecSystems PD-1[35], (e) DeltaQuad Pro VTOL[36]

The aerodynamic and structural analysis of VTOL UAV Systems is extremely important for designing VTOL with optimum Aerodynamic properties for various purposes. VTOLs for mapping purposes need to operate at lower cruise speeds with a high endurance time limit and lower heights and lift, whereas the Attack VTOL Aircraft need to operate at higher speeds and Reynolds number and also need to have a higher lift and better structural strength.

Czyba et. al.[12] designed and created a mathematical model of a Tiltrotor Hybrid VTOL UAV and performed CFD Simulations of the VTOL UAV at low Reynolds number for three modes: (a) VTOL Mode, (b) Transition Mode, and (c) Aircraft Mode. The authors used the SST k-ω turbulence model to analyze the VTOL UAV in a SIMPLE (Semi-Implicit Method for Pressure Linked Equation) Environment.
Fig. 4 Variation of (a) Pitching Moment with Angle of Attack at (Re=237,000), (b) Ratio of Lift to Drag Coefficient at Side wind of (i) 0°, (ii) 5°, (iii) 10°

Fig. 5 Velocity Contour Plots and Wind Velocity vectors for Angle of Attack (AoA) (i) 12°, (ii) 16°

Ozdemir et. al.[9] analyzed the Aerodynamic properties of the TURAC VTOL System. The paper adopted Vortex Lattice Method to analyze the properties of Aerofoil, Propeller, and the Main Wing of the TURAC VTOL System. The optimum Aerodynamic and Structural properties were later evaluated for designing the TURAC VTOL System.
Yuksek et al. [37] presented a transient analysis of a 1/3rd Scale Prototype of TURAC VTOL. The paper presented a linear mathematical model based on the Degree of freedom, Aerodynamic, and Thrust forces for the UAV during the forward flight and transition state (hover to cruise and vice versa). Narducci et al. [38] presented an analysis of V-22 Osprey Tiltrotor Aircraft. The aerodynamic properties of the aircraft prototype was first analyzed using CFD and were later compared and confirmed using Wind Tunnels. Uncertainty in inventory and back orders was handled by [39-44].

The main purpose of this paper is to analyze a Tiltrotor VTOL Unmanned Aerial Vehicle, by designing a VTOL from scratch and analyzing it in a CFD Environment. The paper is organized in different sections: First, the Introduction is provided in Section 1. The selection of aerofoil and design of VTOL UAV is provided in Section 2. Next, the results of the Computational Fluid Dynamics (CFD) analysis of the Tiltrotor VTOL UAV are provided and briefly discussed in Section 3. The conclusions are briefly discussed in the last section.

2. VTOL Design

2.1 Aerofoil Selection

The Tiltrotor VTOL UAV generally operates at low Cruise speeds and low Reynolds number. The Tiltrotor UAV is designed to be tailless and with a high Lift coefficient. For the same reason, Aerofoil NACA 34112 is selected as it has a high Lift Coefficient and imparts the VTOL tailless structure due to the Reflex Camber in the Wing structure.

Fig. 7 NACA 34112 Aerofoil
Table 1. Design Parameter of NACA 34112 Aerofoil

2.2 Plane Design

The Tiltrotor VTOL UAV is designed to be take-off vertically as well as Conventionally. The VTOL UAV has been provided with large blended Wings (with a mean aerodynamic chord of 967 mm) for no stall conditions in transition modes, and higher energy efficient endurance limit, and with no tail elevator or fins owing to the Reflex Camber Aerofoil NACA 34112. Winglets (Sharklets) have been provided at the trailing ends of the wing to increase lift to drag ratio and reduce vortices formation of the air at the ends of wings. The front rotors and the Side rotors are designed to tilt at an angle from vertical to the horizontal plane in different flight modes. The Tiltrotor VTOL UAV specifications have been designed for higher energy efficiency, flight ranges, endurance limit, Payload delivery, and lift as shown in Table 2.

| Parameter                  | Value       |
|----------------------------|-------------|
| Lift Coefficient           | 0.45        |
| Camber Position & Reflex   | 20% reflex  |
| Thickness                  | 12%         |

Table 2. Configuration of Tiltrotor VTOL UAV

| Parameter                  | Value       |
|----------------------------|-------------|
| Configuration              | Tiltrotor VTOL UAV |
| Wing Span                  | 5520 mm     |
| Wing Area                  | 4.238 m²    |
| Plane Mass                 | 4713 g      |
| Wing Load                  | 1.124 kg/m² |
| Mean Aerodynamic Chord     | 0.967       |
| Root Chord                 | 1500 mm     |
| Tail Chord                 | 200 mm      |
| Aspect Ratio               | 7.190       |
| Taper Ratio                | 9.375       |
Table 2. Design Specifications of Tiltrotor UAV VTOL

| Specification                  | Value          |
|-------------------------------|----------------|
| Root Tip Sweep                | 20.008°        |
| Propeller Diameter and Pitch  | 16x8 inch      |
| Maximum Speed                 | 15 m/s         |

Fig. 8 (a) Main Wing of Tiltrotor VTOL UAV, (b) Tiltrotor VTOL UAV

The inertia and COM Calculation is extremely essential for analyzing the Aerodynamic properties and stability of the Aircraft structure. The process of calculating Inertia and COM is an iterative process comprising of placement of VTOL components, and changing aircraft specifications. The inertia and COM calculation of the plane was carried out by treating the masses of various components such as motors, propellers, Flight Controller, Servos as point masses to ease the inertia and COM calculation as shown in fig. The results of Inertia and COM Calculation of the Tiltrotor VTOL UAV are tabulated in Table 3.

Fig. 9 Inertia calculation of the Tiltrotor VTOL UAV
### Table 3. Inertia and Centre of Mass of the Tiltrotor VTOL UAV

| Parameter            | Value          | Parameter | Value        |
|----------------------|----------------|-----------|--------------|
| Total Mass           | 4713 g         | I<sub>XX</sub> | 1.92257 kg.m<sup>2</sup> |
| COG (X-axis)         | 717 mm         | I<sub>YY</sub> | 1.55702 kg.m<sup>2</sup> |
| COG (Y-axis)         | 0 mm           | I<sub>ZZ</sub> | 3.47702 kg.m<sup>2</sup> |
| COG (Z-axis)         | 15 mm          | I<sub>XZ</sub> | -0.00560 kg.m<sup>2</sup> |

### Table 4. Nomenclature

| Symbol | Name                                      |
|--------|-------------------------------------------|
| \( R_e \) | Reynolds Number                         |
| \( C_L \) | Lift Coefficient                        |
| \( C_D \) | Drag Coefficient                         |
| \( C_P \) | Pressure Coefficient                     |
| \( C_m \) | Pitching Moment Coefficient              |
| \( \alpha \) | Angle of Attack                         |
| \( \Phi \) | Velocity Potential Function              |
| \( \partial \) | Delta Operator                          |
| \( t \) | Time variable                            |
| \( \bar{u}_i, \bar{u}_j \) | Mean velocity of Fluid                   |
| \( u'_i, u'_j \) | The fluctuating velocity of Fluid       |
| \( x_i, x_j \) | Position vectors in x, y-direction       |
| \( \nu \) | Kinematic Viscosity of Fluid             |
| I<sub>XX</sub>, I<sub>YY</sub>, I<sub>ZZ</sub> | Inertia around X, Y, Z axis           |
| COG | Centre of Gravity                       |
3. Analysis

To access the aerodynamic properties of the VTOL UAV, a series of Computational Fluid Dynamics simulations were performed in XFLR5. A full platform of the model was created without any symmetric planes for analyzing non-symmetrical interactions such as side wings, vortices formations. Vortex Lattice Method (VLM) was used to analyze the VTOL structure and the aerofoil. For that purpose, the aerofoil was refined globally into 120 individual panels and the VTOL Structure meshed into 120 panels in each direction under Neumann boundary condition and the iterative simulation was run over 100 times for each parameter. As the VTOL has to be analyzed at Low Reynolds number, RANS (Reynolds averaged Navier Stokes) equations were used in the VLM environment.

4.1 Governing Equations

4.1.1 Reynolds averaged Navier Stokes equation

\[
\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{\partial \tilde{p}}{\partial x_i} + \nu \frac{\partial^2 \tilde{u}_i}{\partial x_i \partial x_j} - \frac{\partial (u'_i u'_j)}{\partial x_j}
\]  

(1)

4.1.2 Laplace Equation

\[
\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0
\]

(2)

The nomenclature is provided in Table 4.

4.2 Aerofoil Analysis

For the analysis of the VTOL UAV, the analysis of Aerofoil is extremely important for the selection of design and analysis parameters of the Tiltrotor VTOL UAV. Most VTOL operates at low Reynolds number owing to low cruise or hovers speed and chord length. Keeping this in mind, several simulations from low to high Reynolds numbers are performed on the NACA 34112 aerofoil. The Reynolds number is evaluated using the formula, at the kinematic viscosity of 1.5*10^5 m^2/s:

\[
R_e = \frac{v L}{\nu}
\]

The Reynolds Number at the Plane speed of 5 m/s for the Mean Aerodynamic Chord was found to be 322,330 and at 15 m/s was found to range from 200,000 to 967,000 for Root
Chord and Tail Chord. The Computational Fluid Dynamics Simulations for the aerofoil was first run at (a) Reyn number 322,330 and then (b) from a Reynolds number of 200,000 to 1,000,000. In the first case, the Lift Coefficient, Drag Coefficient, Pitching Moment Coefficient, $C_L$, $C_D$, $C_M$ are presented as a function of Angle of Attack (AoA or $\alpha$) as shown in fig.[10-13]. Next, the Lift Coefficient and the Drag Coefficient, $C_L$, $C_D$ are presented as a function of Angle of Attack at various Reynolds Number ranging from 200,000 to 1,000,000 and vice versa as shown in fig. 14-17.

4.2.1 Aerofoil Analysis at Reynolds Number of $3.22*10^5$

The lift coefficient, $C_L$ increases proportionally from 0° till 14° when it reaches the stall angle, whereas the Drag Coefficient too increases gradually from 0° to 14° and suddenly increases as soon as the Stall angle is reached. The Lift Coefficient, $C_L$ increases while Drag Coefficient, $C_D$ decreases while the aerofoil is in a negative angle of attack giving the aircraft more stability while doing maneuvers as shown in fig. 10-12. The Trim angle is found to be at 0° giving the aircraft better stability rendering it the properties of being tailless. Due to a slight variation at -4°, and 2° in the Pitch Moment Coefficient, a variation is observed in the ratio of Lift to Drag Coefficient as well as in the Drag Coefficient as shown in Fig. 13.

![Coefficient of Lift vs Angle of Attack](image)

**Fig. 10 Variation of $C_L$ with AoA for the Aerofoil at Reynolds Number of $3.22*10^5$**
2.2 Aerofoil analysis at different Reynolds Number

The Lift Coefficient, $C_L$, increases gradually at Reynolds Number $5 \times 10^4$ and $1 \times 10^5$ whereas it increases proportionally from $2 \times 10^5$ to $1 \times 10^6$, whereas the Drag Coefficient increases linearly for
the higher Reynolds Number (2*10^5 to 1*10^6), and increases rapidly at the lower Reynolds Number (2*10^4 to 1*10^5), the sudden increase in the Draft coefficient, C_D and decrease in Lift Coefficient, C_L is due to the aerofoil reaching the Stall angle. The Lift to Drag Coefficient increases rapidly at the higher Reynolds number and then decreases after the stall angle, whereas at the lower Reynolds number the C_L/C_D follows a linear path and decreases till the stall angle as shown in fig. 14-16. As shown in fig. 17, at the lower angle of attack, the lift coefficient, C_L is lesser than 1, and it reduces at the higher Reynolds number. As the AoA increases, the Lift coefficient also increases while giving a maximum Lift Coefficient of 1.6 at the stall angle.

Fig. 14 Variation of C_d with AoA for the Aerofoil at various Reynolds Number

Fig. 15 Variation of C_L/C_d with AoA for the Aerofoil at various Reynolds Number
4.3 VTOL Analysis

The Tiltrotor VTOL Analysis was performed using VLM (Vortex Lattice Method) at the Plane Speed (a) 5 m/s, and (b) 10 m/s. The VTOL surface was paneled into 100 panels in each direction and the Neumann boundary condition was used for the simulation.

4.3.1 VTOL Analysis at Plane Speed 5 m/s

The lift coefficient increases proportionally from 0.1 to 0.4 with the increase in the angle of attack(AoA), whereas the drag coefficient increase gradually from 0° to 2°, and increase rapidly from 2° to 5°, which leads the Lift to Drag Coefficient($C_L/C_D$) to increase till 2° rapidly and then till 4° gradually as shown in fig. 19. The front edge of the VTOL UAV experience a greater Pressure Coefficient($C_p$) than the tail edge at all Angle of Attack as shown in fig. 18. The Streamline flow simulation also shows that the winglets reduce the vortices formation at the end.
of the Tail of the Wing and the surface imparts a rather laminar flow to the Fluid flowing over the wing surface as shown in fig. 20.

**Fig. 18** Variation of Pressure Coefficient at the plane surface at various AoA (a) 0°, (b) 2°, (c) 4° at the plane speed of 5 m/s

**Fig. 19** Variation of (a) $C_L$, (b) $C_D$, (c)$C_L/C_D$ with AoA at Plane Speed of 5 m/s for Tiltrotor VTOL UAV
4.3.2 VTOL Analysis at the Plane speed of 10 m/s

At the plane speed of 10 m/s, the Lift Coefficient, $C_L$ increases proportionally from 0.1 to 0.8, whereas, the ratio of Lift to Drag Coefficient, $C_D$ increase till the angle of 2.2° and then increase gradually till the angle of 5° and starts to decrease after 5° as shown in fig. 21.

**Fig. 20** Flow of the Air over the wing of the VTOL

![Flow of the Air over the wing of the VTOL](image)

**Fig. 21** Variation of (a) $C_L$ with AoA, (b) $C_D$ with AoA, (c) $C_L$ with $C_D$ at the speed of 10 m/s for the Tiltrotor VTOL UAV

![Variation of (a) $C_L$ with AoA, (b) $C_D$ with AoA, (c) $C_L$ with $C_D$ at the speed of 10 m/s for the Tiltrotor VTOL UAV](image)
4. Conclusion

In this paper, the design and analysis of a Tiltrotor VTOL UAV are presented. The VTOL was designed using a reflex camber aerofoil and the wing using a blended design. The CFD analysis presented in this paper gives a broad overview of the aerodynamic properties of the Aerofoil and the VTOL UAV.

In the CFD simulations of the NACA 34112 aerofoil at the Reynolds number 322,330, the following results were observed:

1. The lift coefficient, $C_L$, increases, and the Drag Coefficient, $C_D$, decreases with an increase in the Angle of Attack up to the stall angle.
2. The Lift to Drag coefficient decreases till the Angle of Attack $-4^\circ$ and then increases considerably till $12^\circ$ and decreases till stall angle.
3. The trim angle of the airfoil is found at the Angle of Attack of $0^\circ$.

In the CFD simulations of the NACA 34112 aerofoil at various Reynolds number ranging from $2\times10^5$ to $1\times10^6$, the following results were observed:

1. The Lift Coefficient, $C_L$, increases proportionally at the various Reynolds Number.
2. The Draft coefficient, $C_D$, decreases suddenly at higher Reynolds number, increases suddenly at lower Reynolds number.

The results of the CFD simulations of the aircraft are summarized as follows:

1. At higher Plane speed, a higher Lift coefficient is observed.
2. The winglets reduce the vortices formation considerably on the wing.
3. Higher Pressure Coefficients are found on the front surface of the Wing.

The following research gaps were observed in the specified area:

1. More comprehensive research is needed in the field of VTOL design and analysis for commercial purposes.
2. The effects of the different wing profiles and shapes on the aerodynamic performance of the VTOL UAV must be studied.
3. A detailed research needs to be done in the field of Aerodynamic analysis of Tilting Ducted Fan VTOL UAV.

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