A Review on Design Methods of Vertical take-off and landing UAV aircraft

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Abstract. Unmanned aerial vehicle is the most widely used aircraft technology due to its eminent applications in various fields like in military for surveillance, patrolling and rescue operations, agriculture and civil uses like food delivery, Aerial photography etc. There are two main categories of UAVs; Fixed-wing UAVs and multi-rotor UAVs. There are some issues which arise with conventional aerial vehicles like the absence of enough runway in rural areas and dense forests. Vertical take-off and landing (VTOL) UAVs have the advantages of both fixed-wing and fixed rotor type aircraft. These types of aircraft are more suitable for such applications where lack of runway and dense forests are major issues. This review article mainly focuses on the work done in the domain of design and analysis of vertical take-off and landing (VTOL)

Keywords: Unmanned Aerial Vehicle; VTOL; Runway; TiltRoter; Aerodyne…

1. Introduction

The present automotive industries are focusing on developing such aerial vehicle which operates with minimal human interaction and in a more stable manner. VTOL is one of the technologies which fulfils these requirements. Due to their high payload capacity and automation with sensors make them more suitable for applications like military, rescue tasks, delivery task and aerial photography. The use of these UAVs is more economic than using a manned aircraft for a certain application. there are various types of VTOL UAVs as shown in Fig. 1.

![Fig. 1 Main types of vertical take-off and landing (VTOL) aircraft](image-url)
2.1 **Tilt Wing rotor VTOL** – Tilt wing rotor aircraft is a type of VTOL as it takes-off and land vertically. It has a horizontal wing for conventional forward flight and it rotates during vertical take-off and landing. These types of aircraft utilize the power of the engine more efficiently in lifting the aircraft but they have less hovering capacity and more susceptible to wind gusts as it has a large area to interact with air during its forward flight. A tilt wing experimental aircraft LTV XC-142 which was designed to investigate the stability and performance is shown in [Fig. 2.](image)

![Fig. 2 LTV XC-142 tilt wing VTOL[1]](image)

2.2 **Tiltrotor VTOL** – In this type of VTOL, the propeller remains vertical during the take-off and landing like a helicopter but as the speed of aircraft increases the propellers aligns themselves in the forward direction and provide a forward motion thrust. These aircraft are different from tilt-wing aircraft because in this VTOL the only rotor rotates instead of the whole wing. The prototype of Bell V-280 valor next-gen tilt rotor is shown in [Fig. 3.](image)

![Fig. 3 V-280 Valor next-gen tilt-rotor VTOL[2]](image)

2.3 **Tilting ducted fan VTOL** – In this type of VTOL there are annular-shaped ducts which accommodate the rotors. These types of VTOL exhibit high cruise speed and high hovering efficiency. A high-speed tilting ducted fan VTOL developed by American flights dynamics system is shown in [Fig. 4.](image)
2.4 **Tilt jet VTOL** – This type of VTOL configuration is similar to the tilt-rotor as it has jet engines on both corners of the horizontal wing which can move from vertical to the horizontal position. These types of aircraft can easily perform VTOL action. An experimental German fighter jet EWR VJ 101 of tilt jet type is shown in Fig. 5.

2.5 **Aerodyne VTOL** – It is the first wingless vertical take-off and landing aircraft. In this configuration, there is a ducted rotor which generates the thrust and lift or both for the flight. In the rear part, it has a conventional tail for forwarding flight. A unicraft aerodyne VTOL is shown in Fig. 6.

2.6 **Thrust vector-controlled VTOL** – In this VTOL aircraft vectoring is used to develop a vertical take-off and landing thrust. Vectoring is a phenomenon which is utilized to change the direction of thrust. Now, this vectoring is used in fighter jets also. A thrust vector-controlled VTOL used by US and UK air forces is shown in Fig. 7.
The enhanced applications of VTOL UAVs in various fields attracted a lot of researchers to work on such type of aircraft. The higher hovering efficiency, cruising speed and the payload capacity are the major concerns of researchers. Akturk et. al. [7] investigated the experimental and 3D RANS model-based computational behaviour of ducted fan of a VTOL and concluded that the disk loading computations and total pressure predictions of mean flow at the rotor exit are in good agreement with the experimental results. The author found that the losses were occurring were tip leakage losses, hub region losses and rotor wake losses. Zhou et. al. [8] performed the investigation of analytical behaviour of fixed-wing vertical take-off and landing aircraft with gas-driven fan propulsion mechanism and reported that the proposed propulsion system can provide a range of load for low-speed operations and the energy loss coefficient of propulsion system must be less than 0.2 for an optimized functioning of the system. Dundar et. al. [9] designed a VTOL for low take-off weight and better aerodynamic performance and also investigated the power consumption for each flight condition that are take-off, climbing, cruise and landing. The author compared the fixed-wing concept with multirotor and four extra propellers with conventional fixed-wing aircraft concept and found that simple fixed-wing aircraft have more endurance than the FW VTOL with four extra propellers. Kamal et. al. [10] performed a conceptual design of a transitional VTOL UAV with some incomparable maneuver and attitude capabilities. Jamaluddin et. al. [11] performed the design and analysis of fixed-wing VTOL by arranging all the equipment and motors such that the position of the centre of gravity doesn’t change. The author also compared the thrust that is necessary for hovering and cruising modes individually with the thrust developed by motors. Kubo et. al. [12] investigated the design and transitional flight of tail sitting VTOL. The author developed a design of tail-sitting VTOL by using a non-linear mathematical model. Intwala et. al. [13] performed the design and analysis of vertical take-off and landing aircraft. In this investigation, the author prepared three different models of VTOL then analysed and compared the parameters like total deformation and von misses stress by Ansys analysis software. Bose et. al. [14] performed the design, analysis and the fabrication of a thrust vectoring spherical VTOL aircraft. Muraoka et. al. [15] successfully investigated the aerodynamic parameters of Quad tilt-wing VTOL UAV. Ozdemir et. al. [16] designed a commercial hybrid VTOL air vehicle with detachable and changeable wings. The author performed structural analysis on Ansys software for the optimal size of the VTOL. Stoll et. al. [17] emphasised on the conceptual design of an electric VTOL named Joby S2. Udriot et. al. [18] prepared a conceptual design of a remotely piloted tilt-wing VTOL with the help of software like XFLR and CATIA. Zhao et. al. [19] performed the investigation to evaluate the aerodynamics coefficients and to analyze the different flow patterns at a different angle of attack and speeds for ducted fan VTOL UAV. Uncertainty in inventory and back orders was handled by [20-25].

2. Past methodologies used for the analysis of VTOL UAVs
3. A computational and experimental approach to analyse a ducted fan VTOL UAV.

Akturk et. al. [7] adopted an experimental and computational approach to analyse a ducted fan vertical take-off landing aircraft. A 3d RANS computational model was utilized for a fine analysis of fan rotor under realistic conditions. The author simulated the fan field and secondary flows like wake system, blade boundary layer and tip vortices also. The computational region and the medium size mesh for hovering condition computations are shown in Fig. 8(a) and 8(b). The pressure contour for rotor exit and computational streamlines near the ducted fan at 12000 rpm are shown in Fig. 9 (a) and 9(b).

![Fig. 8(a) Boundary condition and computational domain for hovering condition; 8(b) Medium size mesh for computation](image1)

![Fig. 9 (a) Total pressure contour at the exit of fan rotor; 9(b) Streamline at the ducted fan at 12000 rpm](image2)

The rotor hub geometry has a significant effect on losses and separation which occurs from the corner of the rotating hub. In this work the author has analysed two types of rotor hub geometry one is
without cavity and one is with a cavity at the centre of the hub as shown in Fig. 10 (a) and 10 (b). It was observed by the author that the hub which is having a cavity in the centre exhibits fewer losses as compared to the without cavity rotor hub.

![Image](image_url)

Fig. 10 (a) Streamlines flow simulation for rotor hub without cavity at the centre and step on corner; 10 (b) Streamline flow simulation for rotor hub with cavity and step on corner

3.1 Design and Analysis of VTOL (Vertical take-off and landing aircraft) – In this work the author Intwala et. Al. [13] prepared three different VTOL models and performed the structural analysis for each of them. The author has considered some specific forces during the analysis process as shown in Fig. 11 and Table 1.

| Load | Type            | Magnitude (Kg-f) |
|------|-----------------|------------------|
| A    | Fixed Support   | NA               |
| B    | Thrust Force    | 0.9357           |
| C    | Thrust Force    | 0.9357           |
| D    | Motor Weight    | 0.07             |
| E    | Motor Weight    | 0.07             |
Fig. 11 Force Consideration

Table 2 Simulation results of total deformation and Von Misses stress for model 1, 2, and 3
3.2 Design of a commercial Vertical take-off and landing aircraft— In this work the author Ozdemir et. Al. [16] designed TURAC VTOL UAV aircraft which has two modes; VTOL mode in which the fan remains in open condition and Cruise mode in which the fan remains in close position. The author has given a significant emphasis on performing aerodynamic analysis and presented some very important results. In his study, the author presented the effect of angle of attack on induced drag and lift coefficient for two different airfoils NACA34112 and NACA0015 as shown in Fig. 12 (a) and 12 (b).

![Fig. 12(a) lift coefficient VS Angle of attack; 12(b) Induced drag VS Angle of attack](image1)

The author also simulated the flow of streamlines over the body of the VTOL in both modes for an angle of attack $\alpha = 5^\circ$ as shown in Fig. 13(a) and 13(b).

![Fig. 13(a) Streamlines of TURAC closed fan at $\alpha = 5^\circ$; 13(b) Streamlines of TURAC open fan at $\alpha = 5^\circ$](image2)
Apart from all this the author performed the structural analysis of TURAC and presented the simulation results for total deformation and Maximum and minimum principal stresses as shown in Fig. 14, 15(a) and 15(b).

Fig. 14 Total deformation simulation of TURAC VTOL

Fig. 15(a) Maximum principal stress; 15(b) Minimum principal stress

3.3 A conceptual design approach for a Joby S2 electric Vertical take-off and landing UAV –
In this work, the author Stoll et al. [17] developed a Joby S2 VTOL UAV which operates on the electric propulsion system. The proposed design has two configurations; VTOL configuration and Cruise configuration. The design was performed on XFLR5 software. Initially, the author utilized the blade element momentum theory to analyse the propeller design. Further, the CFD analysis was also performed by the author to investigate the drag, stability and the performance of the propeller. The CFD results for pressure coefficient contour is shown in Fig. 16.
The author also investigated the skin friction coefficient contours for plane nacelle and nacelle with spinner gaps and folded blades as shown in Fig. 17(a) and 17(b). From the results, it can be concluded that the plane nacelle is more efficient to avoid skin friction.

3.4 A conceptual design approach for a highly maneuverable Transitional vertical take-off and landing aircraft with enhanced attitude capabilities- The author Kamal et. Al. [10] prepared a conceptual design of a transitional tilt-rotor VTOL which is supposed to control, trim and propel the UAV in all flight modes and further performed the CFD analysis on Ansys fluent software to verify the aerodynamic properties of transitional VTOL in fixed-wing mode. The medium-mesh generated for analysis and the pressure distribution on the upper surface of Transitional VTOL are shown in Fig. 18(a) and 18(b).
Conclusion – From the time when VTOL came into existence, a variety of VTOL technologies are developing. With the developing technology, all the issues occurring with VTOL are also getting solved. There are some points which are important for future aircraft design scenario –

- As the VTOL is developing more in the military field but it should also rise in the civil application. The low cost of the VTOL aircraft will also be a major concern for people so it must be more economic.
- Nowadays VTOL is a trending technology but there are some traditional aircraft which are more preferable than VTOL for some applications. If traditional technology is more suitable for some application then that technology will be more relevant. Many technologies can be used in a single aircraft to solve the issues.
- In Future for the development of commercial aircraft, a solution like short take-off and landing type aircraft can be more environmental friendly and economic

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