A Review of Advanced High-Speed Rotorcraft

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Abstract. Urban air transportation (private aircraft, air taxi, etc.) and all kinds of special flight missions (aerial sightseeing, logistics transportation, disaster relief, anti-terrorism and anti-riot etc.) put forward high requirements for the flight performance of future urban aircraft. It not only demands high-efficiency hovering performance, but also demands the capability of high-speed cruising as well as high safety, clean energy and other characteristics. The maximum flight speed of conventional rotorcraft (such as helicopter, multi-rotor UAV, etc.) is limited by the fluid compressibility of advancing rotor blade and the airflow separation of retreating rotor blade, which makes further improvement of the flight speed more difficult. In order to overcome the fluid compressibility of rotor advancing side and stall of rotor retreating side encountered under high-speed, researchers have proposed many new concepts of advanced rotorcraft. This article sorts and analyses the current advanced VTOL (Vertical Take-Off and Landing) rotorcrafts with new configurations, and attempts to point out the feasible research direction in the future.

1. Introduction
Conventional rotorcraft (such as helicopter, multi rotor UAV, etc.) has efficient performance in vertical take-off and landing, hover, low-altitude and low-speed flight, as well as the unique capabilities of back and side flight. However, due to the asymmetry of the flow between the left and the right sides of rotor in forward flight, the maximum flight speed is limited by the fluid compressibility of the advancing rotor blade and the flow separation characteristics of the retreating rotor blade [1]. According to the research and analysis of rotorcraft aeromechanics, it is very challenging to design a new type of rotorcraft, not only to meet the high-efficiency hovering performance like helicopter, but also to meet the high-speed cruise capability like fixed wing aircraft, and under reasonable cost. The key factor in the design of such aircraft is rotor disc load. Figure 1 shows the relationship between the hovering efficiency and disc load of different types of VTOL vehicles [2]. It can be seen that the aircraft with lower disk load has better hovering efficiency (such as conventional helicopter, multi rotor UAV, etc.), with the increase of disk load, the hovering efficiency gradually decreases, but the maximum flight speed increases (such as F35B Fighter, Harrier Fighter, etc.). It can be seen that the VTOL performance and high-speed flight capability are contradictory. The design of advanced rotorcraft should consider the trade-off between flight speed, hovering efficiency, manufacturing complexity and cost.
Figure 1. Relationship between hovering efficiency and disc load

For this reason, researchers have made a lot of explorations and attempts, and proposed various new configurations. After decades of development, demonstration, and experiments, the current high-speed rotorcraft mainly adopts three technical solutions: compound high-speed rotorcraft [3–6], rotor/wing conversion high-speed aircraft [7–9] and tilt-rotor (wing) aircraft [10–15]. This article mainly introduces and analyzes the related research of these three technical solutions, and attempts to point out development direction in the further.

2. Review of related work

2.1. Compound high-speed rotorcraft

2.1.1. Winged compound rotorcraft. In recent years, the winged compound rotorcraft that features the fusion of wing and multi-rotor power system has developed rapidly [16]. This kind of rotorcraft is usually equipped with a wing to provide lift together with the rotor at high speed, and the tail rotor of conventional helicopter are replaced by the propeller system with adjustable thrust, as shown in Figure 2.

The core idea of the technical solution of winged compound rotorcraft is: to unload the main rotor through the combination of wing and multi-rotor power system. In hover and low-speed flight, the aircraft operates in helicopter mode. When the flight speed increases to a certain level, the rotor speed will reduce with the rotor unloaded and the wing gradually loaded. At this moment the forward thrust is borne by the propeller system [17]. When the rotor speed is reduced to half, the main rotor generally needs to bear merely 20% of the flight weight, this operation mode is mainly used for high-speed flight [18]. The decrease of the rotor speed and the angle of attack of the blade profile delay the shock stall of the advancing rotor blade and the airflow separation of the retreating rotor blade respectively. The winged compound helicopter not only increases the flight speed and expands the flight envelope, but also greatly reduces the vibration level and improves the manoeuvrability. Figure 2a shows the concept aircraft eCRM-002 proposed by Uber [5]. During vertical take-off and landing, the aircraft provides lift through the coaxial co-rotating rotors of the distributed electric propulsion (DEP) system (the coaxial co-rotating rotors can reduce noise and improve aerodynamic efficiency); when flying at high speed, the rotors of the DEP system are unloaded, the wings are gradually loaded, and forward flight thrust is provided by two propellers located at both tips of the wing. Figure 2b shows the X-49A [19] "Speed Eagle" compound high-speed helicopter, which is modified from Sikorsky’s YSH-60F helicopter. It is equipped with a wing to unload the main rotor, and a ducted fan vector propulsion system to balance the negative torque of the rotor and conduct heading control.

More representative models include Eurocopter’s X3 high-speed compound helicopter (Figure 2c, in the certification stage [3]), Boeing’s PAV (Figure 2d, flight test of scaled prototype [20]), and AutoFlightX’s V600 (Figure 2e, prototype display [21]), Geely Automobile’s TF-2A (Figure 2f, flight
test of scaled prototype [22]), Kitty Hawk Corp.’s Cora (Figure 2g, prototype flight test [23]), and Beta Technologies’ Alia eVTOL (picture 2.1h, prototype flight test [24]).

(a) Uber eCRM-002  
(b) X-49A  
(c) X3  
(d) Boeing PAV  
(e) AutoFlightX V600  
(f) Geely TF-2A  
(g) Cora  
(h) Alia eVTOL

Figure 2. Hybrid compound helicopter

2.1.2. ABC rotorcraft. As early as the mid-1960s, Sikorsky Aircraft Company took the lead in researching an "Advancing Blade Concept" (ABC) rotor [25, 26], aiming to break through the limitations of the working mechanism of traditional helicopter rotor. The design feature of the ABC rotor system is the application of two coaxial rigid rotors rotating in opposite direction, which allow the lift to be moved to the advancing side of the disc, thus the retreating side of the disc can be offloaded at high speeds and therefore avoid blade stalling. A technology demonstrator ABC was tested in the 1970’s (XH-59A, Figure 3a), it is able to achieved speed of 240 knots, but with high vibration and hub drag [26]. Recently, the ABC rotor system has been revisited and the design has been improved through the use of advanced aerofoil sections and active vibration control. Due to these improvements as well as the pusher propeller providing an extra component of horizontal thrust, the Sikorsky X2 (Figure 3b) is able to reach speeds of 250 kt, which is 60% higher than the conventional helicopter [4].
During cruising of Sikorsky X2, the rotor speed reduces to delay the compressibility of airflow of the advancing rotor blade, and most of the engine power is transmitted to the propeller, which is the key to high-speed flight. In order to avoid interference with the operation of the coaxial rigid rotors, the vertical tail is inverted and the rudder is designed to improve the stability and maneuverability of the helicopter. The long horizontal tail wing bends the wing tip down to form two auxiliary vertical tails.

![Image of XH-59A and X2 helicopters](image)

Figure 3. Coaxial compound helicopter

The compound solution of coaxial rigid rotor and propulsion system presents new challenges to rotor structure, material and assembly technology. With the increase of rotor size, the stiffness of rotor blade will decrease. Therefore, the ABC rotor system is not yet applicable for large rotorcraft.

2.1.3. Development direction of compound solution. The compound high-speed rotorcraft is as efficient as that of a conventional helicopter in hover. However, when flying at high speeds, the rotor speed is reduced to delay the compressibility of airflow of the advancing rotor blade, thus the reverse flow region is very large. When the advance ratio is greater than 1, the retreating blades will be mostly in the reverse flow region, which makes the aerodynamic environment very harsh at this time [27]. In addition, due to the configuration of wing and propulsion system, the structural weight increases, and the aerodynamic interference between the wing and the rotor is worse. Therefore, the technology of the compound high-speed rotorcraft needs further research and development, especially in solving the problems of aerodynamic interference and extra structural weight.

2.2. Rotor/wing conversion high-speed aircraft

The development of compound high-speed rotorcraft cannot avoid the asymmetric characteristics of the airflow generated by the rotor. The only way to eliminate asymmetric airflow in forward flight is to stop the rotor rotation, which is the core concept of the rotor/wing conversion high-speed aircraft [7]. This kind of aircraft can completely convert from helicopter mode into fixed-wing aircraft mode, which solves the problem of conventional rotorcraft flight speed limitation.

The stopped rotor / X-Wing rotorcraft proposed by NASA Lewis Research Centre can realize vertical / short takeoff and landing (VSTOL) and high-speed flight at Mach 0.85 [8]. The X-Wing rotorcraft has four rigid blades, which work like traditional rotors when taking off, landing and hovering in helicopter mode. In cruise flight, the clutch separates the engine shaft from the rotor and the rotor is fixed in an "X" shape. The rotor turns into a forward swept and a backward swept fixed wing with an angle of 45 degrees from the fuselage. The engine propels the aircraft by jetting backwards, as shown in Figure 4a. Boeing has developed the X50A "Canard Rotor/Wing" aircraft CR/W [9] (Canard Rotor/Wing), which applies tip jets to drive the blades. After reaching a certain speed level, the rotor stops and locks as a wing shape. During the transition process, the canard and horizontal tail bear the lift, and then the CR/W will fly forward at high speed in the fixed-wing aircraft mode, as shown in Figure 4b.

Compared with the X-Wing, the transition of CR/W flight is very convenient. The horizontal thrust is provided by conventional turbofan engines, which is a perfect combination of half helicopter and half aircraft.
The breakthrough and solution of key technologies such as the airfoil aerodynamic performance, blade control, rotor drive system and rotor/wing conversion technology will bring the development of the rotor/wing conversion aircraft to a higher stage. At present, the above technology is yet difficult and immature.

![Figure 4. Rotor/wing conversion aircraft](image)

(a) X-Wing rotorcraft  
(b) X50A CR/W

2.3. **Tilt-rotor/wing aircraft**

The tilt-rotor/wing aircraft is equipped with one or more pairs of tiltable propeller/rotor assemblies [10–15]. This type of aircraft performs vertical take-off and landing, hovering and low-speed flight in helicopter mode. When the flight speed reaches a certain level, the rotors tilt to horizontal position along with the engine nacelles (or wing). At this time, the wing is gradually loaded, with the rotor unloaded. When the engine nacelles are tilted to horizontal position, the rotors become propulsion propellers, and the aircraft enters high-speed flight in a fixed-wing aircraft mode. In order to balance the hovering performance and high-speed flight performance, the negative twist angle of rotor blade is larger (between -10° of conventional rotor blade and -60° of propeller blade), thus its hovering efficiency is lower than that of conventional helicopter. Tilt-rotor/wing aircraft can be classified into three typical types: tilt-rotor, tilt-ducted fan and tilt-wing.

2.3.1. **Tilt-rotor aircraft.** Tilt-rotor aircraft has good vertical flight and high speed cruise performance. The propeller/rotor blade of tilt-rotor aircraft has a negative twist angle of -40°~ -50°, which can work in a large axial inflow state. In high flight speed, the wing provides lift for the aircraft, and the propeller/rotor is mainly used to overcome the profile drag, as shown in Fig. 5. Research has shown that a tilt-rotor aircraft with advanced technology of rotor airfoil, hub configuration, wing airfoil and fuselage structure weight can reach a maximum flight speed of 740km/h (400kts), twice that of conventional helicopters. The range of conventional helicopter rarely exceeds 1000 km, while the flight envelope of tilt-rotor aircraft exceeds that of helicopter and turboprop aircraft respectively. The operational range of a typical tilt-rotor aircraft V-22 is more than 1850 km. If two more transfer tanks are filled, the range can reach 3890 km.

In the 1980s, the verification prototype XV-15 tilt-rotor aircraft of Bell Helicopter [28] (Fig 5a) successfully verified the feasibility of the tilt-rotor program. In recent years, the V-22 Osprey tilt-rotor aircraft (Fig. 5b) which has been in service with the U.S. Army [29] and the BA609 [30] civil tilt-rotor aircraft developed jointly by Bell and Agusta helicopter company (Fig 5c) show that the tilt-rotor aircraft is the most successful new type of high-speed rotorcraft so far. In addition, the tilt-multi-rotor aircraft with distributed electric propulsion (DEP) system is also relatively rapidly developed, among which the representative aircrafts are: Beta technologies, AVA XC [31] (Fig. 5d) of Inc., which adopts tilt-coaxial rigid rotor system to ensure rotor aerodynamic efficiency under the premise of the body size limitation, has entered flight test stage; Joby S4 [10] (Fig. 5e) of Joby aviation adopts multi-rotor symmetrical design and has entered flight test certification stage. In addition, Uber [6] has proposed the concept aircraft ecrm-001 (Fig. 5f), which refers to the idea of compound rotor aircraft, that is, the rotors on both sides of the wing are set to tilting mode, and the remaining rotors are responsible for providing lift.
In addition, due to the development of DEP program, the multi-rotor can achieve stepwise tilting. That is, part of the rotors tilt into the fixed-wing mode to increase the flight speed, and the others maintain the helicopter mode to keep the lift. For different flight tasks, there can also be a variety of stepwise tilting strategies to complete more efficient flight tasks, and even be achieved in a hovering state.

![Tilt-rotor aircraft](image)

**Figure 5.** Tilt-rotor aircraft

2.3.2. **Tilt-ducted fan aircraft.** In order to further reduce noise and improve safety, many companies have proposed tilt-ducted fan aircraft, among which the representative models (or scaled prototypes) are: Aurora Flight Sciences XV-24A (flight test of scaled prototype [32], Figure 6a) and Lilium Jet of Lilium GmbH (flight test [33], Figure 6b). These two projects integrate multiple small ducted fans on the wing for tilting (DEP configuration), which provides plenty of propulsion redundancy under limited scale. So that safe landing can still be guaranteed in the case of partial power failure. In addition, there are more projects, like Moller International’s Skycar M400 (Figure 6c, in the flight test phase [34]), XTI Aircraft Company’s TriFan 600 (Figure 6d, in the flight test phase [35]), AgustaWestland’s Project Zero (Figure 6e, in the flight test phase [36]) and Bell Helicopter's Nexus 6HX (Figure 6f, prototype display [37]).

Due to the existence of duct, the tilt-ducted fan aircraft can effectively reduce rotor noise. However, according to Figure 1, it can be seen that the weight of the airframe structure will increase because of the duct, and the rotor size is limited, thus the hover efficiency will be decreased.
2.3.3. Tilt-wing aircraft. The principle of tilt-wing aircraft is to change the direction of the rotor thrust by tilting the wing of aircraft to achieve the functions of VTOL and high-speed cruise [38]. Compared with the tilt-rotor, here the wing and the rotors tilt together, so in the VTOL mode, the wing does not have the downward load from rotors, and the payload of the aircraft can be increased. In general, the rotor configuration of the tilt-wing aircraft is closer to the fixed-wing propeller, suitable for axial flow. Therefore, the tilt-wing aircraft can fly faster than the tilt-rotor aircraft in the high-speed cruise mode. However, due to the smaller radius of the blades and the larger load of the rotor disc, the hovering efficiency is lower. In addition, since all the rotor components rely on the wing for tilting, the tilt-wing aircraft cannot perform stepwise tilting, nor can it achieve the tilting process at low speed.

The tilt-wing technology started with the VZ-2 tilt-wing prototype in 1950s, and then the improved XC-142 tilt-wing prototype (Figure 7a) [39] successfully carried out VTOL on an aircraft carrier. The CL-84 tilt-wing aircraft built in the 1960s ~ 1970s has successfully conducted hundreds of flight tests for search, rescue, transportation, and surveillance missions [40]. In recent years, the tilt-wing aircraft using DEP has also been rapidly developed. Among them, the representative aircrafts are: Airbus’s A³ Vahana (Figure 7b, adopting eight-rotor DEP setup, in flight test stage [14]), Opener, Inc.’s BlackFly (Figure 7c, in flight test stage [41]), NASA Langley's Greased Lightning [42] (Figure 7d, scaled prototype flight test stage), and ASX MOBi from Airspace Experience Technologies (Figure 7e, scaled prototype flight test [43]), Flying Gondola of Japan Aeronext Inc. (Figure 7f, scaled prototype flight test [44]), PteroDynamics, Inc.’s Transwing (Figure 7g, tilt-wing plus fold-wing design, to save space when hovering, prototype flight test stage [45]), Bell Helicopter's Autonomous Pod Transport (APT) 70 (Figure 7h, UAV [46], the whole aircraft tilts with wings).

Figure 6. Tilt-ducted fan aircraft
Studies have shown that the structure weight of the tilting mechanism can be increased significantly by using both of variable-pitch rotors/propellers and tilt-wing, especially when the wing is equipped with more than 8 rotor components. Therefore, in order to develop further, tilt-wing aircraft must overcome the above challenges in the future.

2.4. Development of advanced rotorcraft in the future

Based on the research, the current development of mature advanced rotorcraft technology can be divided into the following aspects: the compound technology of mixing the wing and the multi-rotor propulsion system, the tilting rotor technology of changing the direction of the rotor thrust to adapt VTOL and high-speed flight, and distributed electric propulsion (DEP) technology for energy and propulsion redundancy [47–49]. With the development of DEP technology, the propulsion redundancy is effectively improved due to the quantity of rotors. When a certain number of rotors or propellers fail, the remaining rotors or propellers can still ensure a safe landing of the aircraft, or even continue to...
complete flight tasks. Therefore, in recent years, DEP technology has been widely used in the design of new advanced rotorcraft.

The compound high-speed rotorcraft combined with DEP technology can form various advantages. The aerodynamic direction of lift system and thrust system are basically perpendicular to each other, thus the coupling effect is low. Therefore, the control strategy is relatively simple, and the effect of propulsion redundancy of DEP is better. However, its disadvantages are also prominent. This technology requires multiple rotors providing vertical lift and propulsion propellers providing horizontal thrust. Thus, the propulsion system and its auxiliary structures have a high weight ratio, especially, the horizontal propulsion system not participating in the VTOL phase results in more waste of structural weight. In addition, during forward flight at high speed, the rotation velocity of the lift rotor is reduced, thus the reverse flow region gets large. Also, the aerodynamic environment of the rotors gets harsh, which affects the dynamic characteristics of the rotors, the handling quality and the stability of the airframe. Therefore, the improvement of forward speed is also greatly restricted.

The combination of tilt-rotor aircraft and DEP technology forms the tilt-multi-rotor aircraft, which can effectively improve the performance of rotorcraft. Due to the negative twist angle of tilt rotor blade is larger, its hovering performance is lower than that of conventional helicopter. However, the hovering performance of tilt-rotor aircraft can be similar to that of the compound rotorcraft, or even better, owing to all the power systems participating in the VTOL procedure. On the other hand, compared with the compound rotorcraft, all the propulsion systems of the tilt-rotor aircraft can provide horizontal thrust at high speed, and the rotors will not encounter the reverse flow region, which makes the aerodynamic environment more stable and higher flight speed be achieved. In addition, due to the application of DEP technology, multiple rotors can tilt stepwise. That is, some rotors tilt to fixed wing mode to improve flight speed, and the other parts remain in helicopter mode to maintain lift. At different flight speeds, there can make various stepwise tilting schemes to complete flight missions more efficiently.

Therefore, this paper believes that the tilt-multi-rotor aircraft based on DEP technology meets the performance requirements of future VTOL aircraft, especially the urban aircraft. Its characteristics like efficient hovering performance, high-speed cruise capability, long range, long endurance, and high safety, environmental benign, low noise and so on, will be a feasible development direction of the new configuration rotorcraft in the future.

2.5. Key technologies of tilt-multi-rotor aircraft

Tilt-multi-rotor aircraft has obvious advantages in aerodynamic layout and propulsion system, but there are also technical challenges as follows: 1. The tilting process involves changes in the configuration and flight speed, which not only causes complicated unsteady aerodynamic effects on rotors, wings and other components [50], but also causes nonlinear variation in parameters such as the center of mass and inertia of the aircraft, resulting in additional inertial effects [51]. Therefore, the conversion control strategy between helicopter control mode and fixed wing aircraft is also complex [52], especially for a tilt-multi-rotor aircraft. 2. Additional actuating device and auxiliary structure weight are needed for tilting mechanism; 3. When DEP technology is used, the above two key technologies will be more complicated. This is because multi-rotor of DEP system is able to conduct stepwise tilting. Under different flight missions, there can also be various tilting solutions to execute flight missions more efficiently, which makes the design of tilting mechanism more complicated. How to design a reasonable dynamic conversion control strategy, complete the conversion of the two control modes, and design a safe and reliable tilting mechanism under the requirements of lightweight structure of the aircraft are the key technologies of tilt-multi-rotor aircraft.

3. Conclusion

This paper sorts and analyses the current advanced VTOL (Vertical Take-Off and Landing) rotorcraft with new configuration, and attempts to point out the feasible research direction in the future. Research shows that the aircraft with low disk load has good hovering efficiency, but the flight speed
is difficult to further improve, however, with the increase of disk load, the hovering efficiency gradually decreases, but the maximum flight speed increases. In order to resolve this contradiction, researchers have proposed various advanced solutions. After decades of development, demonstration, and experiments, the current advanced high-speed rotorcraft mainly adopts three technical solutions: compound high-speed rotorcraft, rotor/wing conversion aircraft and tilt-rotor /wing aircraft.

The compound high-speed rotorcraft adopts mutually independent lift system and thrust system. Its thrust system can further increase the forward speed, and the control strategy is relatively simple. However, the thrust system cannot participate in hovering, thus the weight of the propulsion system is relatively high, and this solution cannot completely solve the problem of the reverse flow region of the rotor during high-speed flight.

Rotor/wing conversion aircraft turns the rotor into a wing by stopping the rotor, and completely converts from helicopter mode into fixed-wing aircraft mode, which solves the problem of conventional rotorcraft flight speed limitation. However, the key technologies involved are not mature, such as airfoil aerodynamics, blade control, rotor drive system and rotor/wing conversion. Obviously, it is only in the preliminary stage of development.

The tilt-rotor/wing aircraft can switch between VTOL mode and high-speed cruise mode through the tilting of the rotor group, which overcomes the problem of asymmetric airflow on both sides of the rotor during high-speed flight. It is perhaps the most ideal scheme at present. The key technical challenges are the complicated aerodynamic interference, the distribution of control strategy and the design of tilting mechanism.

In addition, distributed electric propulsion (DEP) technology, which considers the safety of energy and propulsion redundancy, has been widely used in the design of new advanced configurations of rotorcraft in recent years, so as to ensure that when 1 or 2 rotors (or propellers) fail, the remaining rotors (or propellers) can still guarantee a safe landing process for the aircraft, and even continue to complete specific flight tasks.

Through a detailed comparison and analysis of the research status, this paper draws a conclusion that the tilt-rotor aircraft combined with DEP technology is a feasible development direction for the new configuration of the advanced rotorcraft in the future. First of all, compared with the compound aircraft solution, all the power systems of the tilt-rotor aircraft can participate in VTOL and high-speed cruise, and the rotor will not encounter the reverse flow region during high-speed cruise, the aerodynamic environment is relatively stable, so it can achieve higher forward speed. Secondly, compared with the rotor/wing conversion aircraft solution, the key technologies involved are more mature and will be easier to implement in the next few years. Finally, compared with the tilt-wing aircraft solution, the multi-rotor system with DEP of tilt-rotor aircraft can realize stepwise tilting, that is, some rotors tilt to fixed wing mode to improve flight speed, while the other parts stay in helicopter mode to maintain lift, so as to improve the safety in the process of tilting. For different flight tasks, there can also be a variety of stepwise tilting strategy to complete flight tasks more efficiently, and even in a hovering state.

Therefore, this paper believes that the tilt-multi-rotor aircraft based on DEP technology meets the performance requirements of future VTOL aircraft, especially the urban aircraft. It has characteristics of high-efficiency hovering performance, high-speed cruise capability, large range, large endurance, high safety, environmental protection, low noise, etc., which is a feasible development direction of the future advanced rotorcraft.

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