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A review of the design of multifunctional light load evtol mechanical structures

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ABSTRACT

As an important vehicle for future urban air transport (UAM), the electric vertical take-off and landing vehicle (eVTOL) provides an innovative solution for short-distance travelling with high efficiency, low carbon and low noise. This paper focuses on the mechanical structure design of the multifunctional light-load eVTOL, systematically reviews its core technology, architectural features and key performance indexes, and analyses the design characteristics and application scenarios of different configurations, such as multi-rotor, tilt-rotor and composite wing. Meanwhile, a comparative study of the range, safety, economy and environmental impact of representative eVTOL models at home and abroad is conducted. The study shows that reasonable aerodynamic layout and lightweight structure optimisation are crucial to improving the range, energy efficiency and commercial viability of eVTOLs. However, the industry still faces challenges such as limited battery energy density, powertrain safety and airworthiness certification. This paper summarises the current state of technology development and evaluates the future direction of development to provide a scientific basis for academic research, engineering practice and policy formulation, in order to promote the maturity and large-scale application of eVTOL technology.

KEYWORDS

eVTOL; multifunctional light load; mechanical structure design; urban air traffic (UAM), composite wing; endurance

1 Introduction

With the acceleration of urbanisation and the increase of ground traffic pressure, traditional transport modes can hardly meet the demand for efficient and sustainable travel in the future. As one of the core technologies for future Urban Air Mobility (UAM), electric vertical take-off and landing vehicles (eVTOL), with its zero carbon emission, low noise and high manoeuvrability, provides a new solution for short-distance urban commuting, emergency rescue and cargo transportation. In recent years, many aviation companies and technology companies around the world have invested a lot of resources in the research and development of eVTOL to promote its technological advancement and commercialisation. However, eVTOLs are still facing many challenges in terms of range, structural optimisation, safety and airworthiness certification. Especially due to battery energy density, how to ensure flight performance while maintaining a lightweight design has become a key issue in current research. In eVTOL design, the optimisation of the mechanical structure directly affects the performance, energy consumption and safety of the vehicle. A reasonable aerodynamic layout can enhance flight efficiency, optimise energy consumption and thus improve endurance. According to different flight requirements, eVTOL has developed three mainstream architectures: multi-rotor, tilt-rotor and composite wing. Among them, multi-rotor design is simple and suitable for short-distance urban air traffic, but with a shorter range; tilt-rotor combines vertical take-off and landing with high-speed cruise capability, but with higher mechanical complexity; composite wing strikes a balance between cruise efficiency and structural complexity, which is considered to be an important direction for the development of eVTOL in the future.

2 Current status of the study

Overseas research in the eVTOL field started earlier, mainly focusing on vehicle architecture optimisation, power system enhancement and airworthiness certification, etc. Joby Aviation adopts a tilt-rotor design (Joby S4) to improve cruise efficiency, while Lilium Jet adopts a distributed electric propulsion combined with a fixed-wing layout to further improve range and flight speed. In addition, companies such as Lilium and Vertical Aerospace are researching high energy density battery and hydrogen fuel technologies to break through the range bottleneck. Meanwhile, the U.S. FAA and Europe's EASA are working on eVTOL airworthiness standards to promote the commercialisation of the technology.

China's eVTOL research has been developing rapidly in recent years, mainly focusing on technology catch-up and commercialisation exploration. EHang has launched a multi-rotor eVTOL (EHang 216), and AutoFlight has developed the V1500M with tilt-rotor architecture and made progress in power system and intelligent flight control technology. At the same time, Yihang 216 has launched short-haul passenger transport pilots in Guangzhou and other places to explore the application mode of urban air traffic. Despite the significant progress made in both domestic and international research, eVTOL still faces challenges such as limited range, insufficient structural optimisation, and imperfect airworthiness certification system, and needs to further explore mechanical structure optimisation strategies to improve the performance and marketability of the vehicle. In general, multi-rotor design is still the mainstream of eVTOL, especially suitable for short-distance, urban air travel and other scenarios, tilt-rotor and composite wing type is more suitable for long-distance urban air traffic, while the vector thrust eVTOL system is complex and has high technical requirements, which leads to its rare application in the civil field.

2.1 Multi-rotor eVTOL

2.1.1 EHang 216

Figure 1 shows the EHang 216 developed by China's Yihang Company, which features a dual-cockpit design + multi-rotor layout with 8 pairs of co-axial rotors (16 rotors) symmetrically distributed around the cockpit; a modular structure that separates the cabin from the rotors, making it convenient for maintenance and upgrades; fully automated piloting; and is designed for completely unmanned operation, making it suitable for short-haul transport and logistics applications. The structure has significant advantages, such as ease of operation: fully automated driving reduces the dependence on the pilot; high safety redundancy, the multi-rotor design allows for safe landings in the event of rotor failure; suitable for multi-purpose use: for urban transport, freight transport and emergency medical transport; however, the drawbacks are equally prominent: limited speed and range, due to the all-rotor design limitations, lower range (35km) and speed (130km/h); limited application scenarios, being more suitable for short distance point-to-point transport, difficult to cope with long distance or efficient cruising needs.

Figure1 EHang 216

2.1.2 Volocopter 2X

Figure 2 shows the Volocopter 2X developed by the German Volocopter Company, with structural features such as multi-rotor layout, Volocity uses 18 small electric rotors distributed on a ring bracket; open frame design, ring bracket structure is lightweight and at the same time has a certain degree of resistance to vibration; modular battery system, the bottom of the battery module can be quickly replaced to improve operational efficiency. The advantages of this structure include high safety redundancy, multi-rotor layout allows single or multiple rotors to remain in flight in case of failure; simplified power transmission structure, no need for complex tilting or aerodynamic transition mechanism to improve reliability; suitable for urban short-haul flights, suitable for low-speed, low-altitude operation in complex urban environments. Corresponding disadvantages include low speed and range, due to the reliance on rotor hovering, lack of fixed-wing cruise efficiency, lower range and speed; higher noise, despite the miniaturisation of the rotors, the large number of them makes the overall noise level still higher than that of fixed-wing designs.

Figure2 Volocopter 2X

2.2 Tiltrotor eVTOL

2.2.1 Joby Aviation S4

Figure 3 shows the Joby Aviation S4 developed by Joby Aviation in the U.S. Its structural features include fixed-wing + six-rotor design, the S4 adopts a combination of fixed-wing and tiltable six-rotor, with the fixed-wing used for cruising and the rotor used for hovering; monolithic composite fuselage, with the carbon fibre composite material to reduce the weight while improving the structural strength and durability; modular rotor bracketThe tilt rotor is integrated with the end of the wing, simplifying the complexity of the tilting mechanism. Advantages of this structure include high energy efficiency, fixed wing provides higher cruise efficiency and longer range (up to 240km) compared to pure multi-rotor design; low noise, low RPM motors and special propellers reduce community noise impact; lightweight design, composite materials and simplified rotor layout reduces the overall weight of the aircraft. Corresponding disadvantages are the complexity of the tilting mechanism, despite the optimised design, the tilting wing adds mechanical complexity that may affect reliability and maintenance costs; limited load capacity, designed for personal or small passenger transport with limited load capacity.

Figure3 Joby Aviation S4

2.2.2 Archer Midnight

Figure 4 shows the Archer Midnight developed by Archer Aviation in the U.S. Its structure is characterised by a fixed-wing + 12-rotor design, with the first six rotors being tiltable for take-off, landing and cruising, and the last six fixed rotors used for hovering; an integrated fuselage design using composite materials and lightweight construction; and a redundant powertrain, with a multi-motor layout to enhance safety. Advantages of this structure include balanced performance, with a good trade-off between range, speed and vertical take-off and landing capability, with a range of 160 kilometres; a high level of safety redundancy, with a large number of motors and rotors, which allows for a certain degree of fault tolerance; and a simple design for urban air traffic, with relatively low operating costs. Corresponding disadvantages include moderate noise levels, with noise control slightly weaker than the Joby S4 in a multi-rotor layout; and limited endurance, with a shorter range limited by battery capacity.

Figure4 Archer Midnight

2.3 Composite wing type eVTOL

2.3.1 Autoflight Prosperity I (V1500M)

Figure 5 shows the Autoflight Prosperity I (V1500M) developed by China's Shanghai Fengfei Aviation Technology Co. Its structural features include fixed-wing + tilt-rotor design, which integrates fixed-wing and tilt-rotor for both vertical take-off and landing as well as highly efficient cruising; a large cabin layout to support multi-passenger transport, and a streamlined fuselage design to optimise aerodynamic performance; and battery Modular, high-energy density batteries are used to support rapid replacement. The advantages of this structure include balanced performance, the tilt-rotor design balances vertical take-off and landing with cruise efficiency, and the range and speed are better than the multi-rotor design; it is suitable for multi-scenario applications: from urban commuting to medium-range transport. Higher passenger capacity, compared to products such as the EHang 216, it can accommodate more passengers and is suitable for commercialised operations. The disadvantages are equally obvious: high complexity of the tilting mechanism, tilting rotor design puts higher requirements on mechanical precision and control algorithms; high cost: composite materials and tilting structure increase the R&D and manufacturing costs; higher maintenance requirements, tilting mechanism requires more routine testing and maintenance, increasing the difficulty of operation.

Figure5 Autoflight Prosperity I (V1500M)

2.3.2 Vertical Aerospace VX4

Figure 6 shows the Vertical Aerospace VX4 developed by Vertical Aerospace of the United Kingdom. Its structural features include fixed wing + tiltrotor propeller, with four tiltrotor propellers designed to combine with the fixed wing to achieve high efficiency in cruising and vertical take-off and landing; streamlined composite fuselage, which optimises aerodynamic performance and enhances cruising efficiency; and the tiltrotor propeller drive system, which is designed for smooth The tiltrotor drive system, designed for smooth transition, reduces in-flight vibration and stress concentration. Advantages of this structure include high energy efficiency: fixed-wing design supports long range, tiltrotor system provides hovering capability; higher passenger capacity, supporting 4-5 passengers, suitable for commercial transport, and strong airworthiness. Corresponding disadvantages include the complexity of the tiltrotor system, which increases mechanical complexity and maintenance difficulties; high R&D and manufacturing costs, composite materials and complex transmission mechanisms that increase the initial investment.

Figure6 Vertical Aerospace VX4

2.4 Vector Thrust eVTOL

Figure 7 shows the Lilium Jet developed by German Lilium, with structural features such as fixed-wing + distributed electric propulsion, 30 electric jet fans in the wing and tail configuration, vertical take-off and landing capability and high-speed cruise performance; streamlined fuselage design to optimise aerodynamic performance and reduce cruise drag; all-electric propulsion technology, using jet fans to provide higher thrust density and low noise performance. All-electric propulsion technology with jet fans provides higher thrust density and low noise performance. Advantages of this structure include long range and high speed, fixed-wing design provides efficient cruise capability with a maximum range of 300km and a cruise speed of 300km/h. Compact propulsion system with fans embedded in the wings and fuselage reduces the risk of external interference and improves aerodynamic efficiency. Modular maintenance design and fans are designed for easy individual replacement or repair. Corresponding disadvantages include high mechanical complexity, with distributed jet fans involving complex electrical and mechanical interfaces, making development and maintenance more difficult;High power consumption, low fan efficiency during vertical take-off and landing, requiring large amounts of power consumption.

Figure7 Lilium Jet

3 Representative eVTOL performance comparison

eVTOL Model \ Performance	flight distance	flight level	smoothness	endurance	charging time	affiliated company
EHang 216	35 km	3,000 m	excellent	20 minutes.	1 hour	EHang
Autoflight Prosperity I (V1500M)	250 km	5,000 m	very excellent	120 minutes.	1.5 hours	Autoflight
Joby Aviation S4	240 km	5,000 m	terrific	120 minutes.	1 hour	Joby Aviation
Volocopter 2X/Volocity	35 km	1,000 m	excellent	20 minutes.	1 hour	Volocopter (Volo flying machine)
Lilium Jet	300 km	3,000 m	fabulous	60 minutes.	1 hour	Lilium
Archer Midnight	160 km	2,000 m	terrific	60 minutes.	1 hour	Archer Aviation
Vertical Aerospace VX4	250 km	3,000 m	very excellent	80 minutes.	1.5 hours	Vertical Aerospace

4 Summary of the study

Multi-rotor designs continue to dominate the market because, among other things, most early eVTOL products used a multi-rotor layout for vertical take-off and landing capabilities, so multi-rotor vehicles do not require runways or complex landing infrastructure, and are suitable for flexible take-off and landing in urban environments, and secondly, a larger number of rotors can effectively increase redundancy, so that even if some rotors fail, the vehicle can still remain stable, with a high degree of safety and redundancy. At the same time, thanks to the maturity of multi-rotor UAV technology, the control system and power system are better applied in eVTOL.

However, as range and speed requirements increased, hybrid layout designs of fixed wing and tilt rotor began to increase, with companies such as Joby Aviation and Lilium Jet using a combination of fixed wing and tiltable rotor. This is because fixed wings offer higher cruise efficiency, extending the range and speed of the vehicle. Compared to a pure multi-rotor design, a fixed wing effectively reduces air resistance and improves energy efficiency. This enables a balance between vertical take-off and landing and high-speed flight. The tilt-rotor design combines the flexibility of vertical take-off and landing with the high efficiency of fixed-wing flight, and is able to meet the demand for longer range and higher speed, making it suitable for medium- and long-distance urban air travel.

Distributed Electric Propulsion (DEP) is also becoming one of the trends in eVTOL design. This system improves control and stability by distributing multiple electric propulsion units at different locations on the fuselage, providing more precise control, especially at low altitudes, improving stability and manoeuvrability. Multiple propulsion systems also provide a high degree of redundancy, so that even if one of the propulsion units fails, the vehicle will still be able to fly stably and land safely. There is also a reduction in noise, as electric propulsion systems are quieter than traditional turbojet engines, which is beneficial for operation in urban environments.

As the commercialisation of eVTOL advances, lightweight design and the use of high-strength composites are becoming increasingly important. Carbon fibre, aluminium alloys and plastic composites have been widely used in vehicle structures, and some designs have explored 3D printing technology. This material structure can reduce weight, and lightweight materials help reduce the overall weight of the vehicle, thus improving the energy efficiency ratio and extending the endurance. Lightweight design is also one of the key factors in reducing the cost of the vehicle and improving operational efficiency. And it also improves structural strength. Composite materials have excellent tensile strength and corrosion resistance, which can reduce weight while ensuring the strength and durability of the vehicle.

5 Challenges and prospects for future development

In response to the several aspects of the study's findings, the following factors were derived as constraints to development in these directions:

For multi-rotor designs, the main challenges centre on limited range, although suitable for short hauls, multi-rotor designs are limited in range and speed. In the future, it may be possible to incorporate more efficient battery technology to improve range, or design optimisation to balance weight and range. Noise: Multi-rotor designs are noisy, especially in urban environments, and may be reduced in the future through optimised propeller shapes, low RPM designs and more efficient electric drive systems.

The main challenge in combining fixed-wing and tilt-rotor is the mechanical complexity; the mechanical design of tilt-rotor systems is more complex, requiring sophisticated rotating mechanisms and flight control systems, which increase development costs and maintenance difficulties. Energy management, despite improved efficiency, energy consumption during transformational flight is still high, and more high-efficiency batteries or hybrid systems may be needed in the future to optimise energy efficiency.

With distributed electric propulsion systems, the main challenge is the battery technology bottleneck. Despite the advantages of distributed electric propulsion in terms of efficiency and redundancy, the energy density of battery-dependent propulsion limits the vehicle's range and endurance, which may be broken through in the future by combining with new battery technologies (e. g., solid-state batteries, hydrogen fuel cells, etc.). The complexity of the power transmission system and the need for complex electrical and mechanical integration technologies for distributed propulsion increase the difficulty of design and manufacturing.

Designing for lightweighting and applying high-strength composites, the main challenge is the high cost of manufacturing; high-strength composites are more expensive to produce, and although they can reduce weight in the overall vehicle manufacturing, the initial investment is large. Materials R&D, new lightweight alloys and smart materials may be explored more in the future to further reduce costs and enhance the overall performance of the vehicle.

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