

The Progress and Application of Aerodynamics of the TOL Modes of Flying Vehicle

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Abstract. In general, flying vehicle represents for hybrid vehicle possesses fixed wing and the ability to fly based on aerodynamics principles. This paper will discuss the aerodynamic technology from the perspective of the application of flying vehicles. Specifically, the aerodynamic concepts such as lift, and wing design will be discussed. Moreover, the current state-of-art of the flying vehicle will be discussed. In addition, the state-of-art specific products will be introduced to help explain the current state-of-art. According to the analysis, the flying vehicle has great prospects. In the future, it is possible to eliminate traffic congestion and relieve pressure on the present metropolitan transportation network by applying this technology. Overall, these results shed light on the guiding the further exploration of flying vehicle in terms of aerodynamics.

Keywords: Aerodynamics, Flying Vehicle, state-of-art products.

1. Introduction

Contemporarily, remarkable progresses have been achieved for of flying vehicle based on the application of Aerodynamics. With the risen of the urban air mobility (UAM) concept in recent years [1], the vertical take-off and landing (VTOL) vehicle, which is used to solve the problem of urban traffic congestion and only has the function of air flight, has been dubbed a flying car, and the concept of a flying vehicle has been expanded to include a vehicle with land and air amphibious function or used for urban air traffic [2]. Flying vehicles can be categorized into two groups based on their takeoff and landing modes: skidding flying cars and vertical takeoff and landing flying cars. They can mostly be divided into combustion flying cars and electric flying cars based on their power source [2]. Since flying vehicles have to be capable of flight, concepts of aerodynamics is used to develop this technology, which will be introduced later in this passage.

Interest in flying vehicles is rising, notably in the United States, after IT giants like Google and Uber took the lead and expressed interest [3]. After years of exploration, flying vehicles are categorized in different groups based on different characteristics and features [4-6]. Flying vehicles can be equipped with numerous operating modes on account of the various types of TOL modes and types of wings available [7, 8]. Electric power, hydrocarbon fuel, and hybrid power are the three main power types for flying automobiles, depending on the application [9].

The motivation of this paper is to present on the advance of aerodynamics technology involved in the flying vehicle, which is a subject that few people researched and wrote about before. This paper will mainly include three parts, the introduction of aerodynamic concepts that are used in flying vehicles, the current state-of-art of flying vehicle technology, and the limitation and future prospect of the flying vehicle.

2. Basic Description

Generally, the flying car can be referred to vehicles that is capable of flying with the compact wings [10]. However, not all of the companies are following this definition to design their products. Yet, all of the flying cars have the flight ability. Due to the flight capability of the flying cars, aerodynamics theories are used to design the flying cars, since aerodynamics is about how to maneuver fast and effectively in a fluid.

Two important forces acting on flying cars are lift and gravity. To combat the weight of the flying cars pushing down towards Earth, lift plays an essential role. It should be noted that lift does not exist without air [11]. The creation of lift can be explained by Bernoulli's equation:

$$P_s + \frac{\rho V^2}{2} = P_t \quad (1)$$

Here, P_s represents the static pressure, ρ represents the fluid density, V represents the velocity of the fluid, and P_t is the total pressure, which is a constant. The equation indicates that throughout the flow [12]. Based on the equation, it can be inferred that the velocity has direct relationship with the static pressure, and the static pressure gets lower as the velocity increases. After the creation of lift is figured out, the lift needs to be calculated. According to the lift equation:

$$L = Cl \frac{\rho V^2}{2} A \quad (2)$$

Here, L is the lift force, Cl is the lift coefficient, ρ is the air density, V is the velocity of the moving object, and A is the wing area [13]. The usage of a single variable to characterize complicated relationships is one method of dealing with them. The lift coefficient, abbreviated "Cl," is the variable for lift, which must be obtained before simulations and calculations [14]. Therefore, based on the lift equation, the design of the wings of the air vehicles should increase the lift while ensuring that the weight is appropriate.

Table 1. Comparisons of different TOL modes [9].

Types	Technical Complexity	Maintenance Cost	Rotary Wings/Vertical Fans	Fixed Wings
VTOL	High	High	Yes	No
VTHL	Medium	Medium	Yes	Yes
HTVL	Medium	Medium	Yes	Yes
HTOL	Low	Low	No	Yes

When it comes to the design of the wings of the flying vehicles, companies have different designs, and it is usually divided to three categories, fixed wings, rotary wings and both fixed and rotary wings. A rotary wing's key benefit is its ability to take off and land vertically (VTOL) [15]. It doesn't require a runway, and according to WIRED magazine, VTOL technology allows planes to take off and land practically anywhere, making them significantly more adaptable [16]. However, there are some drawbacks. To begin with, the rotary wing is inefficient because hovering in place necessitates a lot of electricity to keep the rotors spinning in order to provide the requisite lift. As a result, the maximum payload and flight time are substantially reduced. Second, rotary-wing flying cars go far slower than fixed-wing flying cars. Finally, rotary wings are extremely loud. As for fixed-wing flying vehicles, they travel at a considerably higher speed than rotary-wing flying vehicles. A fixed-wing flying vehicle is also more efficient because, rather than needing a motor to spin the rotary wings. This vehicle can transport significantly bigger payloads and traverse longer distances than a rotary wing because of its efficiency and speed. For takeoff and landing, however, they require extensive runways. Furthermore, hovering is not possible, making air traffic control more difficult in the presence of many vehicles [10]. According to Table 1, it can be clearly seen that the fixed-wing flying vehicle's flying mode is HTOL and the rotary-wing flying's mode is HTOL. Though the HTOL are more flexible in the cities, the maintenance cost is greater than the fixed-wing flying vehicles. Therefore, both designs of the wings have advantages and disadvantages, application of these two designs, or combination of the two designs will be stated later in the paper.

3. State-of-art Application

As the technology of flying vehicle becomes more and more mature, the interest of market in flying vehicle gradually increases, and big companies invest in the flying vehicle companies e.g., aeroMobil, Joby Aviation. With the financial support, the technology might come to us in the near future. PAL-V have the flying vehicle model PAL-V one that is in the production stage, and AeroMobil has the flying vehicle model AeroMobil 3.0 that is in practical prototype stage. As shown in Table 2, different companies have their own product in different stages. This paper is going to list two actual models of flying vehicles, Joby S2 and TF-X to show the current state-of-art of this technology.

Table 2. Sample statement Flying Vehicle models [16].

Flying Vehicle Model	Manufacture	Type of vehicle	Stage
PAL-V One	PAL-V	Gyrocopter road-flight hybrid	Production stage
AeroMobil 3.0	AeroMobil	Roadable monoplane Road-flight hybrid	Practical prototype stage
Ehang-184	Ehang	Autonomous quadcopter	Early prototype stage
Joby S2	Joby Aviation	Fixed wing/tilting electric propellers	
TF-X	Terrafugia	Tilt rotor/fixed wing	

3.1. Joby S2

The S2 would have 12 propellers, eight on the fixed wing and four on a V-stabilizer/rudder arrangement, on tilting and folding nacelles. Aside from accent and decent, the blades would fold back and tilt laterally to decrease drag. For cruising, four more fixed horizontal pusher propellers on the wing and stabilizer tips would be used. The vehicle would have been entirely electric and capable of carrying two people. The choice to stow and fold all lift propellers save those at the wingtips during cruise flight is a major feature of the S2 design. The reason for this is the significant difference in thrust required during hover flight vs cruise. If all propellers remained at cruise, the propellers would be significantly less efficient than they should be, with practically too much blade area for the needed thrust. Instead of requiring variable pitch, the propellers can be constructed for hover/low speed flying by folding them at cruise. This allows each propeller to be set pitch and designed for low tip speed, high solidity blades to provide the lowest feasible community noise. The range of Joby S2 is 322km and the cruise speed is 322kmh.

3.2. TF-X

The TF-X is a four-seat plug-in hybrid-electric flying car that can take off and land vertically. In May 2013, Terrafugia showcased the next-generation TF-X concept aircraft. The TF-X aircraft design is undergoing feasibility studies now. The aircraft will enter service in 2021 after an eight- to ten-year development period. Terrafugia's Transition aircraft will serve as the basis for the new aircraft. It will be made of light materials and will be able to transport four people in car-like comfort. For take-off and landing, a clean 100-foot-radius zone is required. The flying automobile will be able to go on roads and highways, and the vehicle will be small enough to fit in a single car garage. The vehicle will have electrically powered rotors positioned on the ends of fold-up wings and retractable wings. It will be a vertical takeoff and landing aircraft that will take off and land on runways, land strips, and streets. The TF-X aircraft will have cutting-edge intelligent technology and fly-by-wire controls, providing higher levels of personal aviation safety, simplicity, and convenience. This type of aircraft will be able to avoid other planes, adverse weather, and restricted and tower-controlled airspace on its own. When the aircraft is in flight, a 300-horsepower gas turbine engine will power a rear-mounted propeller. The batteries can be charged using the car's engine or by hooking into an electric car

charging station. The landing gear on the aircraft will be retractable. The TF-XT will have a non-stop range of over 800 kilometers (500 miles) and a top speed of 322 kilometers per hour (200mph) [17].

Table 3. Specs of the TF-Transition [17].

Cruise Speed	160 km/h
Range	640 km plus 30 min. reserve
Takeoff Roll	1700 ft (518) over 50 ft obstacle
Useful Load	227 kg
Fuel Burn at Cruise	18.9 L/h
Usable Fuel	87 L
Mileage on Road	6.7 L / 100 km



Figure 1. TF-X from Terrafugia [17].

According to Table 4, the conclusion can be drawn quickly that the operation modes are related to speed. The helicopter-airplane, airplane-car and airplane modes have relatively higher speed than the helicopter-car or helicopter operation modes. It can be also inferred that the flying vehicles that are designed with fixed wings or the combination of fixed wings and rotary wings have higher speed than the flying vehicles that only have the rotary wings.

4. Limitation and Future Prospects

Though applications of flying vehicles have emerged, there are still some existing limitations. First, only when flying cars become more widespread will they be able to meet the goals of reducing traffic congestion and increasing convenience. The development of technology that can reduce the cost of flying cars is critical. Usually, as flying cars grow more popular and mass-produced, the price is projected to drop. Second, flying car noise reduction technology is also developing as a problem to be solved. Third, it is envisaged that popularization will be hastened only when sensor-related technology is created to ensure operational safety, as well as autonomous flight technology capable of flying without human intervention. Fourth, developing battery-related technology for extended flights is critical [3]. Fifth, because the operation space for flying vehicles is typically tens to hundreds of meters above ground. Therefore, flying vehicles face a problem, which is that it might create disturbance to the ecosystem. Sixth, another issue that could come from the widespread deployment of flying automobiles is the infringement of human privacy. Residents may be exposed, viewed, and supervised in the privacy of their own homes and activities if flying cars operate over urban or

residential areas. To protect sensitive areas, such as the airspace over private properties or forbidden zones, flight prohibitions should be imposed. The listed problems above need to be solved in order to achieve further application.

Humans have employed ground, subsurface, and high-altitude space for transportation since the advent of transportation systems. However, in recent decades, as the weight of population development and fast urbanization has increased, the public transportation infrastructure and freight have been under severe strain, troubles the local governments and causes economic anxiety. Engineers and scholars are developing unused near-earth space (NGS) for transportation. With the widespread use of flying cars, it is possible to eliminate traffic congestion and relieve pressure on the present metropolitan transportation network by utilizing uninhabited NGS [9]. Therefore, this technology has great value and is closely related to life. This technology has great prospects; however, the application of such technology must solve the limitations and problems that still exist.

Table 4. Comparison of the state-of-art flying cars [9].

Flying Car	Speed (km/h)	Range (km)	Operation Modes
PAL-V Liberty	160	400	Helicopter-car
Elevate	241.4~370.15	321.87	Helicopter-airplane
Heaviside	—	—	Airplane
Flyer	—	—	Helicopter
The City Airbus	120.70	—	Helicopter
Vahana	190	50	Helicopter-airplane
AeroMobil V. 4.0	360	750	Airplane-car
AeroMobil V. 5.0	—	—	Helicopter-car
VoloCity	80~100	30-35	Helicopter
MOOG	120.7	—	Helicopter
BlackFly	>128.75	64.37	Helicopter-airplane
The Transition	161	644	Airplane-car
The TF-2	230	300	Helicopter-airplane
EHang AAV	130	—	Helicopter
Cora	160	40.23	Helicopter-airplane
Joy Aviation Air Taxi	321.89	241.4	Helicopter-airplane
Jaunt AirCraft	281.664	—	Helicopter-airplane
Passenger Air Vehicle	—	—	Helicopter-airplane
Cargo Air Vehicle	—	—	Helicopter
SD-XX	60	20-30	Helicopter
The Volante Vision Concept	—	—	Helicopter
Moller M400 Skycar	533	1213	Helicopter
The Nexus	241.4	241.4	Airplane
WD-1	201.17	643.74	Airplane-car
DR-7	241	193	Helicopter
The Pop.UP Next	—	—	Helicopter-car
The AirCar	200	—	Airplane-car
S-A1 model	290	100	Helicopter
CityHawk	270	150	Helicopter

5. Conclusion

In summary, this paper discusses the application of aerodynamics theories in the emerging and developing technology, flying vehicles. The paper provides aerodynamics equations to describe the fundamentals of the flight of the flying vehicles, and the paper suggests the relationship between the design of the wings in the flying vehicles with the lift. The paper also discusses three applications of

flying vehicles based on the advantages and disadvantages of the three existing products or prototypes. This paper also analyzes the limitation and future prospects of this emerging technology. It is believed that flying vehicles will relieve pressure on the present metropolitan transportation network by utilizing uninhabited NGS. It is also believed that the actual application of such technology in metropolitan transportation network will soon come as the limitations and problems are fixed. This paper shed light on the progress of aerodynamics of flying vehicle in recent years.

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