PRELIMINARY DESIGN OF VTOL PERSONAL FLYING

MACHINE – DREAMWINGS

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Abstract. This paper presented a conceptual design of novel vertical takeoff personal aircraft for which requirements analysis, initial sizing, analysis of flight performance, cost and potential application prospects are provided. The flight vehicle is named DreamWings, as it is hoped that people’s long-standing dream of flying freely could be realized and the wings of the flying machine are designed to meet this objective. Some common challenges in the design of such a personal aircraft were identified first with analysis on some similar concepts and technology trends. This is followed by requirements analyses, in which, the criteria of the proposed flying machine should meet are outlined. A concept configuration with rotating wing is believed to better meet these requirements. The 3D model of DreamWings was built using OpenVSP. Some preliminary calculations were carried out, along with analysis of challenges and potential solutions. Finally, this paper points out the future tasks and remaining issues for the concept.

Nomenclature

\[ E_{\text{battery}} = \text{Total energy of the battery, J} \]
\[ E_{\text{total}} = \text{Total energy required from takeoff to landing, J} \]
\[ E_{g1} = \text{The energy required to move from the parking place to the vertical takeoff site, J} \]
\[ E_{\text{vto}} = \text{The energy required for vertical takeoff, J} \]
\[ E_{v\rightarrow h} = \text{The energy required to change from the vertical flight state to the horizontal flight state, J} \]
\[ E_{h} = \text{Total energy required for horizontal flight, J} \]
\[ E_{h\rightarrow v} = \text{The energy required to change from the horizontal flight state to the vertical flight state, J} \]
\[ E_{vl} = \text{Total energy required for vertical landing, J} \]
\[ E_{g2} = \text{The energy required to move from the landing site to the parking place, J} \]
\[ \text{FTA} = \text{Number of flight-test aircraft} \]
\[ f_h = \text{Air drag at the level flight mode, N} \]
\[ f_v = \text{Air drag at the vertical take-off and landing mode, N} \]
1 INTRODUCTION

Transportation is playing a major part in modern economy and society, and commercial air transportation is providing increasing comfort for passengers and flexibility for airlines with better economics for long distance travel, in particular. However, a long standing dream of safe, flexible, and economic personal aircraft remains a technical and operational challenge, and a dream to realize. The nature of human body means that it is almost impossible to fly just with human power, development of general aviation aircraft has, to certain extent, met the demands of personal travel, but it generally requires similar facilities as commercial air transportation, albeit on a smaller scale. What is envisioned here is a concept similar to flying car model, but with vertical takeoff and landing capabilities and much improved noise and environmental footprints. Such a vehicle could be used on a daily basis by city dwellers. It could be expected that technology improvements in smart flight operations within confined air space, greener engines, better materials and more efficient aerodynamics are starting to make it a reality, in a not very far future. Such a vehicle should not exceed the size of a familiar car and therefore able to be parked on a parking slot and can take-off and land vertically without the need for a much bigger open space. The noise levels should fall within 80dB, preferable below 75dB to allow its use within cities. The biggest challenge for such vehicles is the air traffic management within city air space where traditional air traffic management technology won’t work. This paper represented an early effort towards the design and eventual operation of such vehicles.

2 RELATED WORK

In 2010, NASA published the design of Puffin, a personal aircraft that uses an electric engine as a source of power, which yields minimal pollution while maintaining high-quality performance. The aircraft’s range is about 80km and the maximum speed is about 240km/h. The noise is 10 times quieter than an ordinary helicopter and the seating capacity is only one person [1]. Its characteristic is that after it takes off vertically, the whole aircraft will rotate before it flies horizontally. The
machine’s advantage is its high speed during the level flight mode while its disadvantage is that the passenger has to maintain a prone position for a long period of time during the flight, which may affect the passenger’s comfort level.

On the other hand, XTI Aircraft Company designed a personal aircraft with a seating capacity of 6 persons. Its range is about 2700km and its maximum speed is about 600km/h [2]. What makes it different is that the two ducted fans beside the wing are rotatable. Its advantages are its high seating capacity and long flying range and its disadvantage are its large parking area and relatively big drag at the vertical take-off mode.

In addition, Martin Aircraft Company designed Martin Jetpack. Its range is about 50km and its maximum speed is about 75km/h. Its seating capacity is only one person [3]. Its advantage is its small size and its disadvantage is its low speed. Another issue is that the passenger is exposed outside, which might be dangerous.

In contrast to Ehang184 produced by Ehang Company, this aircraft is completely autonomous. Its range is about 38km and its maximum speed is about 100km/h [4]. Its seating capacity is one person. The main difference between this machine and the other three examples mentioned above is its independence in control and its ability to fold for parking. However, its range and endurance time are not considered as sufficient for practical operations in addition to the difficulties for the public to accept fully autonomous mode of transportation even though it might have some advantages in terms of eliminating human errors in the operation.

In conclusion, since the research in these types of personal flying machines has just been initiated, most of the concepts still have to be manned. The size is relatively large and the cost is so high that the general public cannot afford it. In addition, the safety record remains to be proven. In the future, the personal aircraft is expected to be safer, more comfortable, more autonomous and more environmental friendly. Similar to today’s private cars, it would become affordable for the public as an alternative mode of transportation, especially between neighboring cities.

3 CONCEPTUAL DESIGN OF DREAMWINGS

3.1 Design process

Top level design parameters of DreamWings were decided first after requirements analyses. This is followed by a configuration study in which multiple configuration designs were compared and analyzed. Some preliminary design on how to fold the wings and the empennage part were carried out. Calculations were done on weight, aerodynamic forces, performance, structure, cost, etc. A 3D model of DreamWings was then built using OpenVSP tool [5]. Lastly, the future tasks and remaining issues for the concept were pointed out.

3.2 Requirement analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Brief explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum seating capacity</td>
<td>2, could be increased to 4</td>
<td>Ordinary private car: 5</td>
</tr>
</tbody>
</table>
Table 1: The desired parameters of DreamWings

- Average weight of a person (kg): 70
- Average weight of adult males: 66
- Total length after folding (m): ≤5.3
- General parking space length: 5.3
- Total width after folding (m): ≤2.5
- General parking space width: 2.5
- Total height after folding (m): ≤2.2
- General underground parking lot height: 2.2
- Total length before folding (m): Calculated
- General parking space length: 5.3
- Total width before folding (m): Calculated
- General parking space width: 2.5
- Total height before folding (m): Calculated
- General underground parking lot height: 2.2
- Fuselage width (m): 0.8-2.5
  - Ordinary human body width: 0.52
- Empty weight(kg): 350
  - Refer to NASA puffin:181 EHANG184:200
- Maximum altitude(m): 1000
  - Relevant policies allow private aircraft to use airspace under 1000 meters
- Maximum level flight speed(km/h): ≥300
  - Refer to NASA puffin:241 EHANG184:100
- Maximum range(km): 300
  - Straight-line distance between Shanghai and Nanjing: 300
    - Between 3-5 hour drive car journey
- Battery energy density(MJ/kg): 0.72
  - Lithium-ion battery: 0.72

The requirements of DreamWings are set for personal private travel. Unlike common private cars, DreamWings includes wings, propellers, and other components. For example, instead of the 5-person seating capacity, the plane’s capacity is set for 2 persons in a front-rear-seat configuration, which allows installation for wings along the span direction.

Next, the parking problem is taken into consideration, the area that the whole plane covers should be restricted within the 2.5m×5.3m rectangular space, the size for common parking spaces for private cars. This limit necessitates the use of folding wings, which will be further explored in the following sections.

For the maximum level flight speed, DreamWings is set for greater than 300km/h as a small fixed wing aircraft is at 300km/h. Since DreamWings should be able to fly between cities, its maximum range is set as about 300km to equal the straight-line distance between Shanghai and Nanjing, cities used in this experiment, such a distance can be covered by one hour compared to current typical car journey of 5-6 hours.

### 3.3 Configuration design

#### 3.3.1 Preliminary overall configuration design

At the vertical take-off mode, the weight of DreamWings should be balanced by the thrust of the propellers. At level flight mode, in order to acquire higher speed, it is better to use the thrust of the propellers as the driving force than to use it to balance the weight which can be instead accomplished by the lift of the wings. The problem is to change the direction of the propeller’s thrust from upward at the vertical take-off mode to forward at the level flight mode.
### Configuration 1

#### Sketches

![Configuration 1 Sketch](image1)

Figure 1: Top view of configuration 1 in VTOF

#### Features

1. Folded wings at the vertical take-off mode
2. Unfolded wings and rotated propellers at the level flight mode

#### Analysis

1. The propellers are easy to be rotated
2. 3 propellers, less structural weight

#### Result

According to analysis, configuration 1 is chosen as the final configuration.

### Configuration 2

#### Sketches

![Configuration 2 Sketch](image2)

Figure 2: Top view of configuration 2 in VTOF

#### Features

1. Fixed propellers
2. The whole aircraft has to be rotated at the level flight mode

#### Analysis

1. The propellers are easy to be rotated
2. 4 propellers, more structural weight

### Configuration 3

#### Sketches

![Configuration 3 Sketch](image3)

Figure 3: Front view of configuration 3 in VTOF

#### Features

1. The whole machine is difficult to be rotated.
2. The posture of the passengers will be rotated, affecting the comfort level for the passengers

### Table 2: Three overall configurations for the design

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Sketches of transformation(all top views)</th>
<th>Features and problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan 1</td>
<td><img src="image4" alt="Plan 1 Sketch" /></td>
<td>Difficult attitude control at the vertical take-off mode and during the rotation of the wing</td>
</tr>
</tbody>
</table>

3.3.2 Empennage design

In order to reduce the structural weight and not to affect the manipulation at the level flight mode, V-tail is adopted. Furthermore, compared to the cruciform tail, the V-tail is more flexible to place the propeller at the rear of the fuselage.

3.3.3 Rotatable and foldable wings and propellers design

![Plan 1 Sketch](image4)
Plan 2  
At the intermediate mode of the rotation of the wing, the wing may block the flow from the propeller so the exact size of every part remains to be calculated.

Figure 5: Plan 2 of DreamWings’s transformation of rotatable and foldable wings

Plan 3  
1. Theoretically feasible
2. More rotatable parts, inducing big structure weight

Figure 6: Plan 3 of DreamWings’s transformation of rotatable and foldable wings

Plan 4  
1. A significant drag during the rotation of the wing as there is a greater windward area.
2. Lift calculation during the rotation of the wing may be difficult.

Figure 7: Plan 4 of DreamWings’s transformation of rotatable and foldable wings

Analysis and result  
The feature of Plan 1-3 is that both the wings and the propellers have to be rotated, which would definitely increase structural weight. Compared to Plan 1-3, the propellers are fixed on the wing in Plan 4. When the wing is rotated, the propellers will be rotated simultaneously, thus having less structural weight. So Plan 4 is chosen.

Table 3: Four plans of rotatable and foldable wings and propellers design

3.4 Sizing of the vehicle (including weight, engine, aero, performance, cost, etc.)

3.4.1 Derivation of mass formula of the flying machine
Total mass:

\[ m_{total} = m_e + m_b + Xm_p \]  

(1)

For conservation of energy:

\[ E_{battery} = E_{total} \]  

(2)

Total energy of the battery:
\[ E_{\text{battery}} = m_b \rho_b \]  

Total energy required from take-off to landing:
\[ E_{\text{total}} = E_{g1} + E_{vto} + E_{v \rightarrow h} + E_h + E_{h \rightarrow v} + E_{vl} + E_{g2} \]  

(4)

For approximate calculation ignoring \( E_{g1}, E_{g2}, E_{v \rightarrow h}, E_{v \rightarrow h} \)
Therefore,
\[ E_{\text{total}} = E_{vto} + E_h + E_{vl} \]  

(5)

(Suppose the air drag \( f_v \) during the vertical take-off and landing mode are the same)
Total energy required for vertical takeoff mode:
\[ E_{vto} = (m_{\text{total}}g + f_v)h_{\text{max}} \]  

(6)

Total energy required for vertical landing mode:
\[ E_{vl} = (m_{\text{total}}g - f_v)h_{\text{max}} \]  

(7)

Total energy required for level flight mode:
\[ E_h = f_h L \]  

(8)

Suppose the lift-to-drag ratio is:
\[ K = \frac{m_{\text{total}}g}{f_h} \]  

(9)

Therefore
\[ m_{\text{total}} = \frac{m_e + X m_p}{1 - \frac{g}{\rho_b} (2h_{\text{max}} + \frac{L}{R})} \]  

(10)

3.4.2 Calculation of the radius of the propeller
Thrust of the propeller is:
\[ T = 2\pi R^2 (V_0 + v_1) v_1 \]  

(11)

From the formula, the thrust of the propeller is proportional to the rotor disk area can be concluded.

Refer to the data of Ehang184. Its maximum take-off mass is 300kg, propeller radius is 0.75m, and the number of propellers is 8. It can be calculated that the mass per unit rotor disk area is about: 21.22kg/m²

Use this data to calculate the radius of the propeller (suppose DreamWings uses double propellers so the number of the propellers is 6). The total area of rotor disk area is \( S = 6\pi R^2 \). The total mass is \( m_{\text{total}} = 21.22 \times 6\pi R^2 \). So the propeller radius is about:
\[ R = \sqrt{\frac{m_{\text{total}}}{20}} \]  

The maximum achievable lift-to-drag ratio based on a typical
propeller aircraft is about 20, so the propeller radius is estimated about 1.5m.

3.4.3 Three views of DreamWings

1. Parking mode

Figure 8: 3D model in parking mode

Figure 9: Top view of parking mode

2. Vertical take-off mode

Figure 10: 3D model in vertical take-off mode

Figure 11: Left side view of vertical take-off mode

3. Level flight mode

Figure 12: 3D model in level flight mode

Figure 13: Center of gravity of DreamWings (top view of vertical take-off mode)
3.4.4 Aerodynamic calculation

First, the lift-to-drag ratio of DreamWings is estimated. At level flight mode, the lift of DreamWings is equal to its total weight and the drag is

\[
D = \frac{1}{2} \cdot \frac{\rho V^2 C}{\mu} \cdot \rho V^2 S + \frac{(1 + \delta)}{\pi AR} \cdot \frac{(m_{\text{total}} g)^2}{2 \rho V^2 S}
\]

The lift-to-drag ratio \( K = \frac{m_{\text{total}} g}{D} \). Using international standard atmosphere model (ISA), \( \rho = 1.225 \text{kg/m}^3, \mu = 1.7894 \times 10^{-5} \text{kg/(m)(s)} \). Suppose the cruise speed of DreamWings is \( V = 100 \text{m/s} \). Chord length \( c = 1 \text{m} \). Wing area \( S = 6.2 \text{m}^2 \). Aspect ratio \( AR = 6.2 \). Refer to Figure 14, for a rectangular wing, \( \delta = 0.06 \). For \( m_{\text{total}} \),

![Figure 14: Induced drag factor \( \delta \) as a function of taper ratio [7]](image1)

![Figure 15: Prandtl’s classic rectangular wing data. Variation of lift coefficient with angle of attack for seven different aspect ratios from 1 to 7. The lift coefficient is 100 times the actual value of the coefficient [7]](image2)

![Figure 16: Characteristics of V-22 Osprey [8]](image3)

![Figure 17: Total cost per aircraft change with number of aircrafts to be produced in five years](image4)
refer to formula (10). It can be calculated that the lift-to-drag ratio of DreamWings is about 20.9 and its total weight is about 630.2kg.

Then, the total thrust of the propellers is calculated. Refer to Figure 16, V-22 has 3 blades for each propeller and the radius of the propeller is about 5.8m. The maximum weight to take off vertically is about 23859kg. It can be calculated that the mass per unit rotor disk area is about 75kg/m² and for Ehang 184, which has been calculated in 3.4.2, is about 21.22kg/m². Refer to these data, the mass per unit rotor disk area of DreamWings is estimated to be about 31kg/m². From Figure 9 and Figure 11, the radiiuses of the 3 propellers of DreamWings are 1.3m, 1.3m and 0.5m, so the total area of rotor disk area is about 22.81m². It can be calculated that the total thrust of the propellers is about 707.1kg.

At vertical take-off mode, the total weight should be balanced by the thrust of the propellers. From the data calculated above, the thrust of the propellers is bigger than the total weight so DreamWings can take off successfully. And it is easy to calculate that the maximum acceleration is about 1.1m/s², so it will take about 1 minute to rise to the height of 1000m. Suppose DreamWings takes off with full thrust, in order to keep it balanced, the center of gravity (refer to Figure 13) can be calculated.

When DreamWings is changing its configuration from vertical take-off mode to level flight mode, the horizontal velocity gradually increases. Refer to Figure 15, the maximum lift coefficient is about 1. Suppose the total weight is only balanced by the lift of the wing, it can be calculated that the minimum flying speed should reach 145km/h. However, at this moment, the wing has not been rotated to the horizontal position completely, so the propellers can also provide some lift. In conclusion, the total lift can balance the total weight at this mode.

At level flight mode, the center of gravity should be controlled in front of the aerodynamic center, so that DreamWings is longitudinal stable at level flight mode, and at the same time, its V-tail can provide enough pitching moment.

### 3.4.5 Cost calculation

A set of cost estimating relationships for conceptual aircraft design developed by the RAND Corporation, known as “DAPCA, IV”, is used here, the methods used is the Modified DAPCA IV Cost Model (engine and avionics costs are ignored here) (costs in constant 1999 dollars) [9]:

\[
\text{Total cost per aircraft} = \\
(445.48 m_e^{0.777} V^{0.894} Q^{0.163} + 635.36 m_e^{0.777} V^{0.696} Q^{0.263} + \\
879.62 m_e^{0.82} V^{0.484} Q^{0.641} + 48.7 m_e^{0.630} V^{1.3} + 1408 m_e^{0.325} V^{0.822} FTA^{1.21} + \\
22.6 m_e^{0.921} V^{0.621} Q^{0.799}) / Q
\]

(13)

where \( Q \) is variable here, \( m_e = 350kg \), \( V = 612\text{km/h} \), \( FTA = 4 \), $1 USD in 1999 would be worth $1.43 USD in 2016.
from Figure 17, if the number of aircrafts to be produced in five years is about 250, the total cost per aircraft is about $1,010,000.

<table>
<thead>
<tr>
<th>Maximum take-off weight (kg)</th>
<th>630.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing area (m²)</td>
<td>6.2</td>
</tr>
<tr>
<td>Wing span (m)</td>
<td>6.2</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>6.2</td>
</tr>
<tr>
<td>Maximum wing loading (kg/m²)</td>
<td>101.6</td>
</tr>
<tr>
<td>Thrust-to-weight ratio</td>
<td>1.1</td>
</tr>
<tr>
<td>Cruise speed (km/h)</td>
<td>360</td>
</tr>
<tr>
<td>Time of rising to 1000m vertically (min)</td>
<td>1</td>
</tr>
<tr>
<td>Cost ($) (50 aircrafts produced per year)</td>
<td>1,010,000</td>
</tr>
</tbody>
</table>

Table 4 Calculated data of DreamWings

4 SOME CHALLENGES AND POSSIBLE SOLUTIONS

One of the main differences between DreamWings and most designs today is that the energy source for our model is battery. It is a great challenge because battery technology will affect its performance drastically.

In the last 20 years, the energy density of lithium-ion battery is approaching the theoretical limit of 250Wh/kg. In order to acquire much higher battery energy density, scientists have great expectations in lithium-sulfur battery, which has a theoretical energy density of 2567Wh/kg. Currently, the energy density of the lithium-sulfur battery developed by British OXIS Company has exceeded 300Wh/kg. The company expects to develop a lithium-sulfur battery twice the energy density of the current lithium sulfur battery. What’s more, hydrogen fuel cells, which have a theoretical energy density of about 3000Wh/kg, were first used in a manned aircraft in 2008. [10, 11, 12].

When calculating the total mass in section 3.4.4, the battery energy density used is the current lithium-ion battery energy density: \( \rho_b = 0.72 \text{MJ/kg} = 200 \text{Wh/kg} \). After analyzing the trend in the development of battery energy density, the value can reach: \( \rho_b = 2.7 \text{MJ/kg} = 750 \text{Wh/kg} \) in the next 5 to 10 years.

As shown from the graph, if the current technology of lithium-ion battery is used, the percentage of battery mass in total mass is about 45%, which is relatively high. In the next 5 to 10 years, the battery energy density can reach twice the energy density of the current battery. The percentage of battery mass in total mass will decrease to about 20%. It is evident that the battery technology has a great effect on DreamWings.

5 CONCLUSIONS

DreamWings can be parked conveniently than other conventional aircraft and it does not need much space to take off and land. Furthermore, it can meet the demands of fast travel between two cities with a typical car journey of about 3-5 hours, which can bring great convenience to the users. After some preliminary calculations and analyses, it can be found that this objective can be achieved in a not so distant future.
However, the realization of this flying machine is also dependent on the development of other technologies and still has large number of challenge to overcome. For example, in order to improve its endurance, a battery with higher energy density is needed. It is hoped that such a concept can provide further motivation for aircraft designers today and in the future.

![Figure 18: Total mass change with battery energy density](image1)

![Figure 19: Percentage of battery mass in total mass change with battery energy density](image2)

**REFERENCES**


[5] OpenVSP is a parametric aircraft geometry tool, which allows the user to create a 3D model of an aircraft defined by common engineering parameters. The predecessors to OpenVSP have been developed by J.R. Gloudemans and others for NASA since the early 1990's.


