Improving Electric Powered UAVs’ Endurance by Incorporating Battery Dumping Concept

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Abstract

Most studies concerning electric powered UAVs’ performance are based on fixed-weight plane model for the fact that battery’s weight remains unchanged during discharging. However, it is possible to extend electric powered UAVs’ endurance by dumping exhausted batteries out of the aircraft in flight. Impact factors affecting the endurance performance of UAV with battery-dumping capability such as the battery dumping system (BDS) weight ratio, battery mounting and dumping device (BMDD) weight ratio, battery packs count and battery dumping strategy were studied and discussed. The optimum endurance with conventional fixed-weight model and battery dumping concept were then obtained and compared utilizing Genetic Algorithm.

Keywords: electric-powered UAV; battery dumping system; duration enhancement; Genetic Algorithm

1. Introduction

Small unmanned aerial vehicles have been proved to be useful and cost effective in both civilian and military applications. Piston-engines and electric motors have served different size of UAVs to fulfill their particular demands. In recent years, electric propulsion system has gained more popularity among small or mini UAVs for its apparent advantages: quiet operation, easy and safe to handle and store, precise power management and control.

Tremendous efforts have been dedicated to the estimation and optimization of electric powered UAVs’ duration and range [1, 2]. These papers however, all share one unshaken precondition - the battery is fixed in the aircraft. As a
consequence, almost every existing method in prediction and optimization of electric UAVs’ performance is based on aircraft with fixed weight. Inspired by piston-engine UAVs whose weight is constantly decreasing in flight as a result of fuel consumption, it would be possible to expend electric powered UAVs’ duration/range by dumping exhausted battery in flight.

In this paper, the battery model was first studied to ensure more accurate prediction of endurance of the UAV. The battery’s discharge rate with different current and power were estimated and recorded to obtain effective capacity and then the influence of the Peukert’s effect was examined. Based on reasonably simplified battery model, and panel methods, the model to evaluate the performance of electric powered mini-UAV was established with XFLR5. Then the performance of the UAV with battery-dumping concept was compared with the conventional fixed weight model.

| Nomenclature            | Definition                                                                 |
|-------------------------|-----------------------------------------------------------------------------|
| BDS                     | battery dumping system. It is composed of battery and BMDD                 |
| BMDD                    | battery mounting and dumping device                                        |
| C                       | battery capacity                                                            |
| CD                      | drag coefficient                                                            |
| CD0                     | zero lift drag coefficient                                                  |
| CL                      | lift coefficient                                                            |
| D                       | drag                                                                        |
| EB                      | battery effective capacity                                                  |
| fs                      | structure weight coefficient                                                |
| m0                      | aircraft mass without electric propulsion system                           |
| mB                      | battery mass                                                                |
| meps                    | mass of electric propulsion system                                          |
| mM                      | motor mass                                                                  |
| mS                      | structure mass                                                              |
| map                     | avionics and payload mass                                                   |
| PB                      | battery power output                                                        |
| Pmmax                   | motor maximum power output                                                  |
| Preq                    | power required to maintain steady level flight                              |
| Rt                      | battery hour rating                                                         |
| S,Sw                    | wing area                                                                   |
| t                       | endurance                                                                   |
| U                       | voltage                                                                     |
| V                       | airspeed                                                                    |
| Vmaxendurance           | airspeed at which the endurance is maximized                                |
| Vminpower               | airspeed at which power required to maintain steady level flight is minimized|
| W                       | take-off weight                                                             |
| α                       | battery weight ratio                                                        |
| αB                      | BDS weight ratio                                                            |
| αBM                     | BMDD weight ratio                                                           |
| ηtot                    | total efficiency of electric propulsion system                              |
| ρ                       | air density                                                                 |

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2. The analysis model

2.1. Endurance of the electric powered mini-UAV

As typical flying envelope of small electric powered UAVs contains a large portion of level flight, we’ll focus on increasing endurance time at level flight condition. In steady level flight, the power required $P_{\text{req}}$ is given by

$$ P_{\text{req}} = D \cdot V $$  \hspace{1cm} (1)

The drag polar for a conventional configuration UAV with cambered wing is more accurate with a shifted parabolic drag polar.

$$ C_D = C_{D_b} - C_{D_1} C_L + C_{D_2} C_L^2 $$  \hspace{1cm} (2)

To maintain stable level flight, the power required $P_{\text{req}}$ is a function of cruise speed $V$ and aircraft weight $W$.

$$ P_{\text{req}} = \frac{1}{2} \rho V^2 S C_{D_b} - C_{D_1} W V + \frac{2 C_{D_2} W^2}{\rho S} $$  \hspace{1cm} (3)

In order to obtain the maximum endurance, we must find the minimum power required to maintain steady level flight. Therefore, if the Eq. (3) derived by speed $V$ equals to zero, then the condition for minimum power can be obtained.

$$ \frac{\partial P_{\text{req}}}{\partial V} = 0 $$

$$ V_{\text{max}}^{\text{endurance}} = V_{\text{min}}^{\text{power}} = \left( x + \sqrt{x^2 + 3 / \chi} \right)^{1 / 2} (C_{D_2} / C_{D_b})^{1 / 2} (2 \rho S)^{1 / 2} $$  \hspace{1cm} (4)

Where

$$ x = C_{D_1} / (2 \sqrt{C_{D_b} C_{D_2}}) $$  \hspace{1cm} (5)

In order to cover as much distance as possible, especially for surveillance application, the plane has to fly at maximum lift-to-drag ratio condition.

$$ E_{\text{max}} = \left( L / D \right)_{\text{max}} = 1 / \left( 2 \sqrt{C_{D_b} C_{D_2}} - C_{D_b} \right) $$  \hspace{1cm} (6)

The power source of electric powered UAV is battery. Lithium polymer battery is the most widely used battery in electric powered UAV for its relatively high energy density and high discharge rate. Electric propulsion system can take up to 60% of the UAV weight [3].

The Peukert's law, presented by the German scientist W. Peukert in 1897, expresses the capacity of a lead–acid battery in terms of the rate at which it is discharged. As the rate increases, the battery's available capacity decreases [4]. The Peukert’s effect exists in rechargeable battery and has a potential influence on electric-powered UAVs, for
higher power output translates to smaller effective energy capacity. The battery discharge time accounting for the
effect of discharge rate is given by \[1\].

\[
t = \frac{Rt}{i^n \left( \frac{C}{Rt} \right)^n}
\]  \hspace{1cm} (8)

Rt is the battery hour rating (1 hour in our case)
The output power of battery is given by

\[
P_B = Ui
\]  \hspace{1cm} (9)

Substitution of Eq. (8) into Eq. (9) yields

\[
P_B = U \frac{C}{Rt} \left( \frac{Rt}{t} \right)^{\frac{1}{n}}
\]  \hspace{1cm} (10)

Electric propulsion system converts stored electric energy in battery to propulsive power of the aircraft and there
will be power losses in every subsystem. The electric propulsion system’s total efficiency \(\eta_{\text{tot}}\) is assumed to be 50%
constantly [2].

2.2. Lithium Polymer battery model

In order to discover discharging character of Lithium Polymer battery, discharging tests on 2200mAh and
3000mAh 3S lithium polymer battery were conducted with constant current and constant power output. Ittech It8816
DC electronic load instrument was implemented to attain and record output data with high resolution of 0.1 mV and
0.01 mA. All data was recorded in the lab with air conditioner to ensure constant temperature.

![Fig. 1. Effective capacity at different discharge rate.](image-url)
The Peukert’s effect exists in different types of battery and has a potential influence on electric-powered UAVs [4], since higher power output results in smaller effective capacity. Lithium polymer battery’s effective capacity is also sensitive to temperature and Peukert’s law.

However, from Fig. 2, it can be found that the maximum deviation of battery capacity is within 0.5% when discharging current and power varied. This may result from a combined influence of discharging heat and Peukert’s effect. Since the power output studied in the experiments well surpasses the power needed for takeoff, climb and cruise flight discussed in this paper, the effect of the discharging current and power on effective capacity is neglected in this paper.

Therefore the coefficient n in Eq. (10) is set to 1 throughout this paper. The discharge platform of lithium polymer battery is generally linear, as shown in Fig.3. The discharge gradient stays almost the same whereas the constant term changes slightly according to discharge power. Even though the voltage of battery keeps dropping during discharge, the voltage stays around 11.1V. Therefore the battery voltage is assumed to be a constant and is kept at 11.1v.
2.3. Aerodynamics Model

The aerodynamics analysis is performed by XFLR5, whose 2D airfoil analysis is exactly the same as XFOIL code and 3D plane analysis is done based on mixed 3D panels/VLM methods for mini-UAVs and model sailplanes. The implementation in XFLR5 has been shown to provide similar and validated results to other comparable codes and wind tunnel results [5, 6].

The mini-UAV discussed in this paper has a conventional tail-wing combination with wingspan of 2.5m and wing area of 0.6m². The design cruising speed is 18m/s and the drag polar is then obtained through XFLR5

\[ C_D = 0.0214 - 0.0386C_L + 0.0746C_L^2 \]  (11)

2.4. Structure

The weight of proposed UAV is given by

\[ W = (m_0 + m_{eps})g \]  (12)

Where \( m_0 \) is the mass of aircraft structure \( m_s \), avionics and payload \( m_{ap} \).

\[ m_0 = m_s + m_{ap} \]  (13)

The structure weight is subjective to the take-off weight, and in our study, the structure weight coefficient \( f_s \) is 0.3.

\[ m_s \cdot g = f_s \cdot W \]  (14)

The mass of electric propulsion system that consist of battery and electric motor.

\[ m_{eps} = m_B + m_M \]  (15)

The battery weight ratio is defined as follows

\[ \alpha = \frac{m_B \cdot g}{W} \]  (16)

Capacity of lithium polymer batter is the function of battery mass. We collected data from Ace Battery and the capacity is approximated as

\[ E_B = 13.006m_B - 0.2818 \text{ (Ah)} \]  (17)
The electric motor’s maximum output power can also be approximated as a function of motor weight. We collected these data from Scorpion motor.

\[ P_{M_{\text{max}}} = 6364m_M - 185.37 \]  

(18)

The total efficiency of electric propulsion system in this paper is set as a constant, 0.5. Such an efficiency is achievable by carefully choosing and coordinating each electric propulsion subsystems [2].
3. Results and discussion

3.1. Endurance estimation with fixed battery weight

Loading the electric powered UAV with larger capacity batteries doesn’t necessarily mean a longer endurance, because heavier weight will result in higher power demand that may offset the additional energy brought by larger capacity. A typical battery weight ratio and endurance relationship is demonstrated in Fig.6.

3.2. The effect of Battery dumping concept

3.2.1. The Effect of battery pack count

For long endurance electric powered UAV, the electric propulsion system can take up 60% of the vehicle weight [3]. If the weight of the battery can be reduced like fuel being consumed in piston-engine powered UAV, the endurance can be improved. One possible way to achieve such concept is to divide the battery into battery packs and dump exhausted ones out of the aircraft. However, the battery dumping system will bring additional weight and power consumption, this will cancel the benefit obtained from variable battery weight. So it is necessary to characterize such a battery dumping system (BDS) and discuss the effect of this system on the endurance.

BDS consists of battery packs and battery mounting and dumping device (BMDD). The battery packs are mounted to BMDD so that only one battery pack is in connection with the electric power system. The BMDD should be able to monitor the voltage of each battery pack. When BMDD found that battery pack in use is about to be exhausted, it will automatically switch and connect to another battery pack while disconnecting and dumping the used one. BDS should be designed and mounted appropriately so that when a battery pack is dumped, the center of gravity of the airplane doesn’t change much.

The BMDD weight ratio is denoted as $\alpha_{BM}$, it is given by

$$\alpha_{BM} = \frac{W_{BMDD}}{W_{BDS}}$$  \hspace{1cm} (19)

The battery pack weight is then given by
The BDS weight ratio is then denoted as $\alpha_B$ and is given by

$$W_B = (1 - \alpha_{BM}) \cdot W_{BDS}$$  \hspace{1cm} (20)

From Fig.8, it can be seen that the power needed to maintain level flight will reduce if battery packs are dumped during flight. The larger the battery weight ratio, the more benefit the BDS will bring as can be seen from Fig.7. Dividing the battery into more packs will increase endurance. However, each battery pack contains connectors and wires; therefore if the batteries are subdivided into too many packs, the effective capacity will be reduced. It also worth noticing that the discharge rate will increase dramatically as the battery is divided into different packs. The battery discharge rate should be restricted to safe level. It can be seen from Fig. 9, for the case when battery weight ratio is 40%, the power needed to maintain level flight drops from 52.04w to 31.16w. It is reduced by more than 40%. We can also find that the endurance is first increased as the battery pack count goes up to 5. The endurance improvement then drops. This is because each battery pack has wires and connectors. The more the battery packs, the heavier the wires and connectors and hence the effective capacity of the battery pack reduces. Another reason could be that all small size electric powered UAVs fly at relatively low Reynolds number. Dumping battery pack will result in lower speed and lower Reynolds number. The combined influence of reduced effective capacity and lower Reynolds number may account for the negative endurance improvement at low battery weight ratio and it can be seen in Fig.7.

Fig. 7. Endurance improvement of aerodynamic model incorporating BDS system in different battery weight ratio $\alpha$ (The battery pack count is 2)
Fig. 8. Power needed to maintain steady level flight for battery weight ratio $\alpha=0.4$. The power will reduce as more battery packs are dumped out of the aircraft (the battery pack count is 5).

Fig. 9. Endurance improvement with different battery pack count; the battery weight ratio is 0.4 in this case.

3.2.2. The effect of the BMDD weight ratio

The weight of BMDD will cancel the benefit from reduced battery weight in flight. From Fig. 7, it can be seen that for the test cases discussed in this paper, when the BDS weight ratio is less than 15%, there is no point incorporating BDS at all for the endurance will only be reduced. When the BDS weight ratio is greater than 15%, there will be net endurance gain from BDS and it allows a certain degree of $\alpha_{BM}$. For aerodynamic model whose BDS weight ratio is 40%, the margin for net endurance gain is approximately 21% as can be seen in Fig. 10. It means that if one fails to design a BDS with BMDD weight ratio smaller than 21%, the endurance would be degraded instead of being improved.
3.2.3. Endurance optimization with Genetic Algorithm

It is tempting to apply the battery-dumping concept to the established aerodynamic model and examine the endurance benefit. In order to achieve more accurate and realistic estimation, the structure weight of the aerodynamic model is assumed to be 30% of the total take-off weight, and the avionics and payload are set as a constant-0.8kg. The weight ratio of the BMDD ($\alpha_{BM}$) is set to be 0.06 for two battery packs and 0.09 for three battery packs respectively.

The optimized endurance for conventional fixed weight model and battery-dumping model have been obtained through Genetic Algorithm.

| Model types                      | Endurance ($h$) | Enhancement |
|----------------------------------|-----------------|-------------|
| Fixed weight model               | 4.38            | --          |
| Battery-dumping 2 batteries      | 5.05            | 15.3%       |
| Battery-dumping 3 batteries      | 5.15            | 17.6%       |

From Table 1, we can see that by incorporating battery-dumping concept, the endurance of the electric powered UAV is extended by 17.6%. The battery dumping strategy is also considered in Genetic Algorithm. And here the dumping strategy refers to the weight percentage of each battery pack. It was found that the optimal dumping strategy is not dividing the battery into even packs. However, the endurance enhancement is less than 1% if we divide the battery pack according to the optimal dumping strategy. Dividing the battery into even packs also simplifies the BMDD design and may result in even lower $\alpha_{BM}$ and longer endurance.

4. Conclusions

Impacting factors that affect the performance of such a UAV with battery-dumping concept such as the battery dumping system (BDS) weight ratio, battery mounting and dumping device (BMDD) weight ratio, battery pack count and battery dumping strategy were studied and discussed. According to the analysis, the following conclusions can be reached:
Increasing the battery weight ratio doesn’t guarantee improved endurance performance of electric powered UAVs. Since increased battery capacity will also induce increased weight. Hence there is optimal battery weight ratio.

By dumping exhausted battery packs, the endurance of electric powered UAV could be extended, provided that the battery weight ratio is greater than a threshold value. The higher the battery dumping system weight ratio \( \alpha \), the more significant endurance improvement can be obtained.

The endurance will be enhanced with increasing battery pack count first, then the endurance improvement over baseline design will drop. It can be seen that there is upper limit for this parameter.

The weight ratio of the BMDD (\( \alpha_{BM} \)) will cancel the benefit from battery dumping. \( \alpha_{BM} \) has to be as small as possible to ensure net endurance gain.

Dividing the battery into even packs is not the optimal battery dumping strategy. Yet the benefit is marginal and may result in more complicated BMDD design. Thus dividing the battery into even packs may be more practical.

Comparing with conventional fixed-weight optimization method, the endurance of the UAV in case was extended by 17%.

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