Wing Flap Suction Window Drone Design

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Abstract. In view of the heavy task, high risk, and high cost of glass cleaning in high-rise buildings, designs a flapping-wing suction window drone (FSWD). The principle analysis of the drone is carried out. Flapping-wing structures are designed, and a window wiper module equipped with a cleaning device. Then, based on the strip method, the aerodynamic characteristics of the drone are analyzed. The pk5008F vacuum pump is used to achieve adsorption walking function. Finally, the workflow of the window cleaning drone is introduced. The FSWD designed this time overcomes the drawbacks of traditional cleaning methods, is safe, efficient, and saves manpower and material resources, and has a good development prospect.

1. Introduction

Because of its unique method of generating lift, flapping aircraft has attracted many people from both home and abroad. In 2000, SRI International teamed up with the University of Toronto to study Mentor, which uses artificial muscle (EPAM) to provide energy for the system. In 2007, Caltech and Aero Environment jointly developed the "Micro-Bat" flapping machine. The UAV carries a miniature camera to monitor the surrounding environment; In 2011, AeroVironment designed the "Hummingbird" [1], which has good flexibility and anti-interference, and can be operated under a wind speed of 2.5m/s; In 2017, the Georgia Technology Research Institute (GTRI), Cambridge University and ETS Laboratories jointly developed a flapping-wing machine “Entomopters” [2]. The aircraft is powered by a reciprocating chemical muscle (RCM) that generate a 10Hz vibration frequency, but it can not fly for a long time because of limited fuel.

Domestic research on the micro flapping wing aircraft started late. In 2005, Hou Yu and others developed a flapping-wing machine, which uses alternating current to drive the wings to beat up and down at a certain frequency and the control is relatively simple. In 2009, Bi Shusheng of Beijing university of Aeronautics and Astronautics constructed a flapping wing transmission device based on a spatial crank rocker mechanism which greatly improved the flutter flap symmetry compared with planar rocker flapping mechanism. In 2015, Chen Shijie proposed a torsion mechanism that adjusts the wing of a bionic flap-to-air vehicle alone to complete the torsional movements such as changing the viewing angle, hovering and receding [3]. In 2017, Zhang Songling and others designed a bionic flapping reconnaissance drone for remote monitoring [4], which can be used for disaster relief and transmission of rescue information.
2. Design Concept
The work is mainly designed based on two aspects:

One is a suction flapping wing drone. Wing flapping is a flying pattern that is commonly used by flying organism in nature. It can generate lift and thrust at the same time by relying on flapping of the airfoil. It has the advantages of high flight efficiency, good maneuverability, and compact structure. Moreover, for wiper applications, fixed-wing and rotary-wing drones are not easily implemented, and the flying characteristics of flapping-wing drones are more suitable.

The second is a self-propelled window cleaner. After the drone flew to the designated location, the wiper module mounted on it began to perform cleaning tasks. The window cleaner is powered by the battery in the drone and it can be firmly adsorbed on the glass by its own vacuum pump or fan unit. When the window cleaner walks on the glass, it drives the cleaning cloth to wipe the glass so as to achieve the purpose of cleaning the window. At the same time, the window cleaner also has the function of automatically planning the path and detecting the corners of the window.

3. Drone Structure Design
The FSWD is composed of a flight part, an adsorption part and a cleaning part. The flight part is a flapper-type aircraft that provides basic flight function. The suction part is located inside the window wiper, which can adsorb the drone on the glass and power the window wiper. The cleaning part is a cleaning device that is mounted on the drone. The overall structure is shown in Fig. 1:

3.1. Flight Wing Design
The FSWD flight part refers to the adult goshawk fin exhibition. The structure of the goshawk wing is shown in Fig. 2. The drone wingspan designed this time was about two meters. To ensure that enough lift was generated, we designed the wing of the drone to be slightly wider than the wings of the goshawk. The design parameters are shown in Fig. 3:

![Figure 1. Structure of a flapping wing suction drone.](image)

![Figure 2. Adult Goshawk Wings Screenshot.](image)
Fig. 4 shows the basic model of this flapping wing drone. One of the most significant features of flapping wings is that the wings can simultaneously provide the lift and thrust necessary to maintain the flight during the flutter. Considering only the uniform linear motion of the UAV in the horizontal direction, according to the aerodynamic force generation method, the aerodynamic forces of the tiny strips of the span can be divided into the following aerodynamic forces: $dN_c$, additional mass force: $dN_a$, and frictional resistance: $dD_f$. The aerodynamic model [5] is shown in Fig. 5.

The Rukovsky lift is the generated by the loop around the airfoil and is the main source of aerodynamic forces during the flight [6]. Its direction is perpendicular to the direction of flow after synthesis, and its size can be determined according to the Kuta-Ruckersky theorem [7]:

$$dN_c = \frac{1}{2} \rho v^2 C_n(y) c dy$$  \hspace{1cm} (1)

In the formula: $\rho$ for air density; $C_n$ for lift coefficient; according to thin airfoil theory: $C_n(y) = 2\pi \alpha$. The additional mass force can be simply described as the force acting on the airfoil when the air in the virtual cylinder surrounding the strip flutters, and is a non-loop force due to the relative motion of the air flow and the airfoil [8]:

$$dN_a = \frac{1}{4} \rho \pi c^2 v_N dy$$  \hspace{1cm} (2)

Where $v_N$ is the normal speed at the midpoint of the strip: $v_N = v_\phi + v_{\infty} sin\theta - 2v_\gamma$. There is also a frictional resistance of the air flow to the strip in the tangential direction of the strip. The formula is:

$$dD_f = \frac{1}{2} C_{Df} \rho v_T^2 c dy$$  \hspace{1cm} (3)

Where is the tangential velocity at the midpoint of the strip: $v_T = v_{\infty} cos\theta + w sin\theta$, $C_{Df}$ is the coefficient of frictional resistance of the plate when it is moving in air: $C_{Df} = \frac{2 \times 1.328}{\sqrt{Re}}$. 

Figure 3. Wings of a window drone.

Figure 4. Drone basic model.

Figure 5. Drone aerodynamic model.
Decompose $dN_c, dN_a$ and $dN_f$ in vertical and horizontal directions, respectively. Superimpose all aerodynamic forces to obtain vertical lift $dF_L$, horizontal thrust $dF_T$ and lateral forces $dF_Y$ of flapping wing drone during flight[9].

\[
\begin{align*}
    dF_L &= (dN_c \cos \alpha + dN_a \cos \theta + dD_f \sin \theta) \cos \varphi \\
    dF_T &= dN_c \sin \alpha - dN_a \sin \theta - dD_f \cos \theta \\
    dF_Y &= (dN_c \cos \alpha + dN_a \cos \theta - dD_f \sin \theta) \sin \varphi
\end{align*}
\] (4)

Lateral force $dF_Y$ provide centripetal force when turning. In the horizontal forward flight state, both wings flutter symmetrically and the lateral forces cancel each other. When the drone turns, the force on one side is greater than on the other side, completing the steering of the drone [10]. The lift and thrust of the tiny strips are integrated according to the span length, and the aerodynamic forces of the left and right airfoils are taken into account at the same time. The total lifting force $F_L(t)$ and total thrust $F_T(t)$ of the flapping wing drone can be obtained at a certain moment. The lift and thrust at this moment are integrated in the flutter cycle $T$ and averaged to obtain the average lift $\bar{F}_L$ and average thrust $\bar{F}_T$ in a complete flutter cycle. From the average lift $\bar{F}_L$ and average thrust $\bar{F}_T$, the overall flight performance of the flapping wing drone can be evaluated [11].

\[
\begin{align*}
    \bar{F}_L &= \frac{1}{T} \int_0^T F_L(t) \, dt \\
    \bar{F}_T &= \frac{1}{T} \int_0^T F_T(t) \, dt
\end{align*}
\] (5)

The obtained mechanical equations were added to the model, then simulated aerodynamics were solved and the results were output. The aerodynamic lift curve is shown in Fig. 6.

**Figure 6.** Aerodynamic lift curve.

In addition, the window drone is powered by an electric motor during the flight, allowing wings to provide lift for the entire device. The powered device is shown in Fig. 7 below.

**Figure 7.** Power plant.
3.2. Adsorption Structure Design

The sorption structure is located inside the window wiper, which adsorbs the drone onto the glass and powers the window wiper (overcoming the overall gravitational force). Fig. 8 is a schematic view of a window wiper. The four corners of the window wiper are equipped with a pressure sensor for sensing the pressure generated by the adsorption force. If the pressure is too high, the rotation speed of the high-speed vacuum off-core fan is increased, and the pressure between the window cleaner and the glass is reduced. Surrounded by a high-fiber rag, a soft silicone dusting strip is placed between the upper and lower fabrics to scratch stubborn stains on the glass and enhance cleaning. Four anti-drop sensors are arranged at four corners to prevent the window wiper from moving out of the glass and the whole device is then dropped from the glass. The drive wheel provides the entire device with mobile power so that the window wiper can move freely on the glass to efficiently clean the high-altitude glass.

![Figure 8. Window wiper structure.](image)

The design of the sorption structure is a key part of the drone capable of performing window cleaning operations at high altitudes. Its main component is the high-speed vacuum core-separating fan. Its structure is shown in Fig. 9. Its rotational speed can reach 19,000 rpm, and the colloid vacuum is 2.8 kPa. The uniform suction generated is sufficient to allow it to absorb objects equivalent to 4.5 times its own weight. The adsorption force it generates must be able to carry weight vertically, because the suction force provided by the pump is mainly used against self-gravity.

![Figure 9. Fan structure.](image)

The suction force is calculated based on the overall weight of the drone and the sucker area (effective contact area with the sucked object). The formula for the suction force is as follows:

\[
F = PS
\]  

Suction force = suction pressure × Contact area

(Suction force unit: kg force; Suction pressure: 0.01 × (The vacuum degree of 100 vacuum pump (absolute pressure)), unit: kilograms of force per square centimeter; Contact area unit: square centimeters.)
Different pump produces different suction forces, so the principle of choosing a vacuum pump is: In the same sucker area, if lighter objects are absorbed, select PK5008, \( F = 0.5 \text{Kgf/cm}^2 \); if medium weight, select PH2506B, \( F = 0.75 \text{Kgf/cm}^2 \); if heavier, select VCH1028, \( F = 0.9 \text{Kgf/cm}^2 \).

Of course, for the same pump, the method of increasing the number of suction cups can also be used to increase the entire suction force, but the corresponding time to reach the desired suction force also increases. Our flapping suction window drone weighs 4kg, and the pk5008F can be used to achieve the adsorption and walking function.

3.3. Cleaning Design

The design of the cleaning section mainly includes two parts: one is a soft silicone duster. It is difficult to judge the difficulty of dust cleaning on high-altitude glass. With such a soft silicone dusting strip, even difficult-to-clean dust can enhance the cleaning effect. The second is a high-fiber rag for cleaning the general dust from the upper glass. The special wedge cross-section allows it to capture even micron-sized dust particles more effectively. This two-pronged approach will clean the upper glass cleaner and increase the cleaning rate. The overall structure of the window wiper is shown in Fig. 10.

![Overall structure of the window wiper.](image)

**Figure 10.** Overall structure of the window wiper.

4. Drone Workflow

The FSWD can be operated by the operator with a remote control handle to control the movement of the drone, and can also set a key mode for the drone to perform each step of the action. The overall flow chart is shown in Fig. 11.

![Cleaning window drone work flow chart.](image)

**Figure 11.** Cleaning window drone work flow chart.
**Step 1** After the window cleaning drone receives the window-wiping task, it flies to the mission location. At this time, the drone's cleaning device and suction device are hidden inside the fuselage. When the drone is about to reach the mission site, tilt the fuselage, gradually approach the window and open the housing at the bottom of the fuselage so that the window cleaner protrudes from the inside of the fuselage, as shown in Fig. 12. When the drone is about to reach the destination, it first opens the housing at the bottom of its body, and then extends the telescopic rod to extend the window wiping part and the adsorption part until the wiping part is parallel to the wall surface (as shown in Fig. 13).

![Figure 12. Drone opens the fuselage.](image1)
![Figure 13. Extend the window wiper.](image2)

**Step 2** After the aircraft was absorbed onto the glass, the shaft began to recover (as shown in Fig. 14). And the head is turned down to enter the standby state. At this point, the drone's preparation for cleaning the glass has been completed and it is ready to work (as shown in Fig. 15).

![Figure 14. Drone absorb to the wall.](image3)
![Figure 15. Drone Standby state.](image4)

**Step 3** Then, the drone started working and cleaned the glass by sucking it. The window wiper can directly control the wiping path by the remote control handle; it can also open the one-touch wiping mode, and only need to select the wiping manner. When the window wiper wipes the glass automatically, it can be wiped vertically or horizontally. As shown in Fig. 16 below:

![Figure 16. Window wiper state](image5)
![Figure 17. UAV Glide to Ground State](image6)

**Step 4** When the glass wall surface of the area is cleaned, the cleaning section and the suction section stop working. The UAV flies directly to the ground (as shown in Fig. 17). If there are other cleaning tasks, the UAV will also glide first to gain the power to fly and then fly to the next mission location.
5. Drone Parameters
The parameters of flapping wing suction drone are shown in the following Tab.1:

| Wing flap suction window drone |  |
|-------------------------------|--|
| Body length                   | 0.6m |
| Wings wingspan                | 2.2m |
| product weight                | 4Kg  |
| Wiper size                    | 22cm×22cm |
| Power support                 | Motor suction: 40-50N |
|                              | Lift provided by the motor: 80N |
| route plan                    | N, Z etc. path |
| glass thickness               | ≧3mm |
| Minimum use area              | 50mm×50mm |
| Applicable interface          | Glass, marble, wood finishes, etc. |
| noise                         | 70dB |

6. Conclusion
In this paper, the principle analysis and structural design of the drone were first performed. The aircraft adopts a flapping-wing structure, carries a wiper window module, and has an adsorption structure inside. At the same time, four corners are equipped with a pressure sensor to sense the magnitude of the adsorption force to prevent falling. The window wiper is surrounded by a high-fiber rag and attached with a soft silicone duster to scrape stubborn stains and enhance cleaning. Secondly, the aerodynamic characteristics and adsorption performance of the flapping-wing drone are briefly analyzed. Finally, the working flow of the designed FSWD is described in detail.

Drone flight technology has gradually matured. The vacuum cleaning glass cleaner’s cleaning ability and cleaning efficiency have been far higher than manpower. The FSWD will have a good development prospect because of its safe and efficient characteristics.

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