Research Article

Dynamic Simulation and Conceptual Layout Study on a Quad-Plane in VTOL Mode in Wind Disturbance Environment

Fan Li ¹, Wen-Ping Song,¹ Bi-Feng Song,¹ and Jun Jiao²

¹School of Aeronautics, Northwestern Polytechnical University, Xi'an, China

²Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing, China

Correspondence should be addressed to Fan Li; lifan0715@foxmail.com

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Quadrotor fixed-wing hybrid vertical take-off and landing (VTOL) UAV, the so-called Quad-Plane, is susceptible to wind disturbance during the VTOL mode, which reduces its stability and limits its application. In order to dynamically analyze its response characteristics to wind disturbance and effectively optimize the wind disturbance rejection performance in VTOL mode, a dynamic flight simulation system based on the 6-DoF equations is established, in which the aerodynamic model of the Quad-Plane is established based on the wind tunnel test, the axial and lateral forces and moments of the rotor in wind disturbance are obtained through CFD simulation, and the Brushless DC (BLDC) motor, wind disturbance, and flight controller are modeled based on actual characteristics. The simulation system is verified and validated by comparing the simulation results with test results of a 5 kg real Quad-Plane. Using this system, the response characteristics of the Quad-Plane to the discrete and continuous wind disturbance are studied. In addition, the influences of major conceptual layout parameters that affect the wind disturbance rejection performance, such as take-off weight, weight distribution, Center of Gravity (CG) position, rotor incline angle, arm length, and arm angle, are studied. Finally, the approaches on designing a Quad-Plane with better wind disturbance rejection performance during the conceptual layout design are presented.

1. Introduction

UAV has been greatly developed in the past decades and is widely used in various application fields, such as cargo transportation, reconnaissance, power inspection, rescue, mapping, and aerial photography [1–3]. There are two main types of flight mechanics, one is multirotor and the other is fixed wing. The advantage of the multirotor UAV lies in its vertical take-off and landing capability, while the fixed-wing UAV performs higher flight speed and longer duration compared with multirotor UAV. In order to combine the advantages of both, several new types of UAVs, such as tilt-wing [4–6], tilt-rotor [7–10], Quad-Plane [11–14], tail-sitter [15, 16], and other types [17] have been the focus of attention by researchers. Among them, the Quad-Plane has achieved a good balance among flight performance, VTOL capability, and controllability, with less system complexity but better stability and safety. It is a kind of UAV widely used and studied at present [12, 13].

UAVs are increasingly widely used in cities, mountainous areas, highlands, and other areas with unstable wind conditions. The impact of the wind disturbance on UAV has become more and more significant [18–21] and has gradually become the main cause of UAV crashes [22], especially in VTOL mode, the Quad-Plane is easily affected by near-ground wind disturbance, so it is difficult to maintain its stability in the air, not to mention completing the mission. Moreover, it might even crash.

Although the aerodynamic shape of the fixed-wing UAV is complex, the flight airspeed direction is nearly coinciding with the longitudinal symmetry plane in most cases. For the multirotor UAV, although the flight airspeed vector does not always coincide with the symmetry plane, its aerodynamic shape is relatively simple, and the aerodynamic forces and moments acting on the body are relatively small. However, the Quad-Plane is often subjected to the wind disturbance from the asymmetric plane in VTOL mode; the effect of the wind disturbance will be more intense. Moreover, the

Quad-Plane has a similar aerodynamic shape as the fixed-wing UAV, but also equipped with the quadrotor system, the hybrid configuration will make the aerodynamic forces and moments acting on the Quad-Plane more complicated than those two kinds of UAVs. Therefore, it is necessary to study the flight performance and stability of the Quad-Plane in the VTOL mode under the wind disturbance to broaden the application range of the Quad-Plane and improve its reliability.

The Quad-Plane can be considered as a nonlinear time-varying system. And some researches focus on the stability of nonlinear time-varying system subject to nonlinear disturbances [23, 24]. The operation and control methods of the Quad-Plane are similar to those of the multirotor UAV in VTOL mode. At present, many studies have focused on the influences of the wind disturbance on multirotor UAVs. Literatures [3, 18, 25–28] devoted to improve the wind disturbance rejection ability of the quadrotor UAV from the aspects of control algorithm design by flight simulation. He and Duan [29] utilize the Active Disturbance Rejection Control (ADRC) to address the problem of height fluctuation in the pitch control of the Quad-Plane, and the Multi-Strategy Pigeon-Inspired Optimization (MSPIO) algorithm is employed in parameter tuning of ADRC. Wang and Sun [30] proposed an incremental adaptive sliding mode control (I-ASMC) to solve the potential rotor failures and improved robustness and make the proposed I-ASMC promising for enhancing Quad-Plane safety. Gunarathna and Munasinghe [31] studied the influence of different take-off modes on the power consumption of the Quad-Plane by flight simulation; the results showed that the UAV could achieve altitude and airspeed while consuming lower energy in the “bird” mode. In References [32, 33], the blade element momentum theory (BEMT) is adopted to model the thrust and torque of the rotor, and the influence of the tilted rotor disk on reducing the pitching moment of the quadrotor UAV is studied. Park et al. [22] established a 6-DoF simulation model of the quadrotor considering gust and flight conditions, calculated the performance of the rotor by means of BEMT considering the rigid blade flapping, and obtained the control parameters of the quadrotor through system identification. Galway et al. [34] studied the effects of urban gusts on the flight performance of Aerosonde UAV. According to the flight simulation, the Aerosonde UAV's heading changes slightly at a wind of 3.89 m/s. Daisuke [35] introduced the method of generating gusts in the wind tunnel to record the response of the quadrotor under gusts by a camera.

According to the above researches, most of them use simulation methods to study how to improve the stability of UAV in wind disturbance. The aerodynamic model of multirotor UAV is often simplified because of its simple aerodynamic shape. The fixed-wing UAV often works in the cruise mode at a small angle of attack and sideslip; however, the aerodynamic shape of the Quad-Plane is complicated, and it will always be subjected to the wind disturbance from lateral and other directions in VTOL mode, so the response characteristics of the Quad-Plane to the wind disturbance in VTOL mode is more sophisticated. Neverthe-

less, there are very few researches published on the dynamic flight simulation of the Quad-Plane in wind disturbance. Meanwhile, in the flight simulation, most of the attention is paid to the control algorithm, and the important parameters such as aerodynamic forces and moments under the wind disturbance are simplified. Moreover, the influences of the conceptual layout parameters of the quadrotor system on the response of Quad-Plane to the wind disturbance also need to be studied in detail. However, these are often ignored because of the model simplification. Compared with the above-mentioned literatures, the most notable feature of this paper is to obtain the dynamic response characteristics of this type of UAV in wind disturbance and the concept layout design ideas of improving the stability in the wind disturbance. To the best of our knowledge, this is the first paper to study the concept layout problem of the Quad-Plane with respect to the stability under the wind disturbance by flight simulation.

Since the wind disturbance varies dynamically with time, we propose a dynamic flight simulation system to study the flight performance and stability of the Quad-Plane in VTOL mode under the wind disturbance. On this basis, the main factors affecting the flight performance in the VTOL stage can be studied and analyzed to gain a better design. At the same time, because the wind disturbances in the real world are different each time, the experimental conditions are hard to be identical in each flight test. Based on the flight simulation approach, the identical disturbance conditions can be generated in each simulation so that researchers can analyze the wind disturbance responses of different designs under the same wind disturbance conditions. The wind disturbance contains various scales of motion of the atmosphere, and their formation mechanisms and development processes are different. Based on the current studies on wind disturbances [36–40], the discrete wind disturbance represented by the 1-cos model and the continuous wind disturbance represented by the Von Karman model are introduced in this paper. The discrete wind model has simple mathematical expression, few variables, and good repeatability, which can be quickly obtained in flight simulation programs to evaluate the flight performance of aircraft against the sudden large load [40]. The continuous wind disturbance model is closer to the real wind disturbance in nature, but since its description is more complicated than that of the discrete wind, it costs much more computational resources to generate continuous wind disturbance than discrete wind.

In order to design a more stable Quad-Plane, make it have enough stability in the wind disturbance in VTOL mode, a flight simulation approach on the Quad-Plane under atmospheric disturbance is proposed in this paper based on our previous work [41]; the Quad-Plane flight performance and stability in VTOL mode under wind disturbance and furthermore the influence of major conceptual layout factors that affect the wind disturbance rejection performance of the Quad-Plane are studied. The test case of this paper is a Quad-Plane with the take-off weight of 5 kg, and the conclusions obtained are applicable to general Quad-Planes.

The contributions of this paper are as follows:

- (1) The calculation method of the lateral forces and moments of the quadrotor system when it is subjected to the atmospheric disturbance oblique to the rotor plane is derived, which improves the simulation accuracy of the quadrotor system
- (2) A dynamic flight simulation system of the Quad-Plane is established, including high-precision sub-modules of aerodynamic, rotor, BLDC motor, wind disturbance, and flight control, which can analyze the response characteristics of the Quad-Plane under the wind disturbance effectively
- (3) The evaluation criteria of wind disturbance rejection performance of Quad-Plane is presented, and the dynamic response characteristics to the discrete and continuous wind disturbance are studied
- (4) Based on the flight simulation system, the main factors that need to be considered in the design process of the Quad-Plane, such as take-off weight, mass distribution, CG position, and quadrotor system layout, are studied, and the approaches on designing a Quad-Plane with better wind disturbance rejection performance in the conceptual layout design are presented

2. Modeling

The simulation system includes the submodels of 6-DoF frame, rotor, wind disturbance, aerodynamic, BLDC motor, and flight controller.

2.1. Systems of Axes and Notation. Let $o^e x^e y^e z^e$ denote the earth-fixed NED axes, $o^b x^b y^b z^b$ denote the body axes, $o^a x^a y^a z^a$ denote the wind axes, and $o^{ri} x^{ri} y^{ri} z^{ri}$ denote the axes of each rotor, where i refers to the index of the rotor from 1 to 4, as shown in Figure 1. The o^{ri} is at the center of the corresponding rotor plane, and $o^{ri} y^{ri}$ is in the rotor plane and parallel to each arm, the direction of which is shown in Figure 1. $o^{ri} z^{ri}$ is parallel to each rotor shaft and points downward; $o^{ri} x^{ri}$ is defined by the right-handed rule. The rotor incline angle between $x^{ri} o^{ri} y^{ri}$ and $x^b o^b y^b$ is denoted as ε , which is generated by inclining the rotor plane around $o^{ri} y^{ri}$ axis, as shown in Figure 2. The distance between the o^b and the o^{ri} is called the arm length and denoted as l_{arm} , and the angle between the arm and $o^b x^b$ is called the arm angle and denoted as ξ .

Let $\Gamma = [x^e, y^e, z^e]^T$ and $\Theta = [\phi, \theta, \psi]^T$ denote the position and attitude of the Quad-Plane. The groundspeed of the Quad-Plane is expressed as $\mathbf{V}^e = \dot{\Gamma}$, the projection of that on body axes is $\mathbf{V}^b = [u, v, w]^T$, and the angular rate is $\omega^b = [p, q, r]^T$. The relationship between $\mathbf{V}^b$ and $\mathbf{V}^e$ and between $\dot{\Theta}$ and ω^b can be expressed as

$$\begin{aligned}\dot{\Gamma} &= \mathbf{R}_{eb} \mathbf{V}^b, \\ \dot{\Theta} &= \mathbf{T} \omega^b,\end{aligned}\tag{1}$$

where

$$\begin{aligned}\mathbf{R}_{eb} &= \begin{bmatrix} \cos \theta \cos \psi & \sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi & \cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi \\ \cos \theta \sin \psi & \sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi & \cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi \\ -\sin \theta & \sin \phi \cos \theta & \cos \phi \cos \theta \end{bmatrix}, \\ \mathbf{T} &= \begin{bmatrix} 1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi \sec \theta & \cos \phi \sec \theta \end{bmatrix}.\end{aligned}\tag{2}$$

2.2. Flight Dynamic Frame. In the body axes, the 6-DoF dynamic equation based on Newton–Euler approach is described as

$$m(\dot{u} + qw - vr) = F_x^b,$$

$$m(\dot{v} + ur - pw) = F_y^b,$$

$$m(\dot{w} + pv - uq) = F_z^b,$$

$$\dot{p}I_{xx} - I_{xz}(pq + \dot{r}) + qr(I_{zz} - I_{yy}) = M_x^b,$$

$$\dot{q}I_{yy} + I_{xz}(p^2 - r^2) + pr(I_{xx} - I_{zz}) = M_y^b,$$

$$\dot{r}I_{zz} + I_{xz}(qr - \dot{p}) + pq(I_{yy} - I_{xx}) = M_z^b,\tag{3}$$

where F_x^b , F_y^b , and F_z^b are the resultant forces acting on the Quad-Plane in the body axes, M_x^b , M_y^b , and M_z^b are the resultant moments in the body axes, the I_{xx} , I_{yy} , and I_{zz}

FIGURE 1: The systems of axes used in simulation.

FIGURE 2: The definition of the rotor incline angle.

FIGURE 3: The oxyz axes of the rotor.

are the moment of inertia about $o^b x^b$, $o^b y^b$, and $o^b z^b$ axes, and the I_{xz} is the product of inertia about $o^b x^b$ and $o^b z^b$ axes.

The resultant force and moment come from three main parts: gravity, aerodynamic forces, and moments acting on the body, and rotor.

The force of gravity in body axes can be expressed as

$$\mathbf{G}^b = \mathbf{R}_{eb}^{-1} \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} = \begin{bmatrix} -mg \sin \theta \\ mg \sin \phi \cos \theta \\ mg \cos \phi \cos \theta \end{bmatrix}. \quad (4)$$

The aerodynamic forces and moments of the Quad-Plane in the body axes are defined as $[F_{aerox}^b, F_{aeroy}^b, F_{aeroz}^b]$ and $[M_{aerox}^b, M_{aeroy}^b, M_{aeroz}^b]$.

2.3. Rotor Model in Oblique Flow. In most of the existing UAV simulations, only the axial forces and moments of the rotor are considered. However, when the Quad-Plane works in VTOL mode under the wind disturbance, the wind speed is parallel to the ground in most cases, and the rotor is subject to the oblique flow inclining to the rotor plane, which will produce nonnegligible lateral forces and moments in the direction parallel to rotor plane [42–44]. Let $oxyz$ denote the single rotor axes, as shown in Figure 3. The forces and

FIGURE 4: The relationship between $oxyz$ and $o^ri x^ri y^ri z^ri$ axes.

moments of the rotor can be decomposed into ox , oy , and oz axis, which can be expressed as

$$\begin{aligned} \mathbf{F}_{oxyz}^{\text{rotor}} &= [F_x^{\text{rotor}}, F_y^{\text{rotor}}, F_z^{\text{rotor}}], \\ \mathbf{M}_{oxyz}^{\text{rotor}} &= [M_x^{\text{rotor}}, M_y^{\text{rotor}}, M_z^{\text{rotor}}], \end{aligned} \quad (5)$$

FIGURE 5: 16 × 5.4 rotor model at 4 m/s wind, where black dots denote sample points of the CFD results at 4 m/s wind.

where the subscript **oxyz** denotes that the forces and moments are defined in *oxyz* axes, and the *ox* axis coincides with the projection of the wind disturbance $\mathbf{V}_a$ onto the rotor plane, as shown in Figure 4. The oblique angle ϑ is used to describe the angle between the rotor shaft *oz* axis and the wind disturbance vector. Therefore, the forces and moments of the rotor are both the function of the magnitude of the wind disturbance V_a , rotor speed Ω , and oblique angle ϑ :

$$\begin{aligned} \mathbf{F}_{\text{oxyz}}^{\text{rotor}} &= F(V_a, \Omega, \vartheta), \\ \mathbf{M}_{\text{oxyz}}^{\text{rotor}} &= M(V_a, \Omega, \vartheta). \end{aligned} \quad (6)$$

To calculate the $\mathbf{F}_{\text{rotor}}^{\text{oxyz}}$ and $\mathbf{M}_{\text{rotor}}^{\text{oxyz}}$, based on our previous work [41], a CFD-based model of the 16 × 5.4 rotor by using surrogate method embedded in DACE [45] is established with the range of $\vartheta \in [45^\circ, 135^\circ]$, $\text{RPM} \in [1000, 6000]$, and $V_w \in [0, 12](\text{m/s})$. This model has three variables, so it is a 4D model and is invisible in 3D space. In order to represent the model in the figure, we fix $V_w = 4 \text{ m/s}$ for example, to reduce a dimension to make the model visible in the 3D figure, as shown in Figure 5, where the black dots denote the sample points.

During the flight simulation, the speed of each rotor Ω_i is given by the electric quadrotor system, and V_a is the airspeed of the Quad-Plane. Thus, the oblique angles between airspeed and each rotor plane ϑ_i are the only unknown and can be calculated as the following steps:

Let $\mathbf{V}_w = [V_{wx}, V_{wy}, V_{wz}]^T$ denote the wind disturbance velocity vector in the NED inertial axes, $\mathbf{V}^b = [u, v, w]^T$ denote the groundspeed vector in the body axes, and then the airspeed of the Quad-Plane $\mathbf{V}_a$ in the body axes $\mathbf{V}_a^b = [v_{ax}^b, v_{ay}^b, v_{az}^b]^T$ can be expressed as

$$\mathbf{V}_a^b = -\mathbf{R}_{eb}^{-1} \mathbf{V}_w + \mathbf{V}^b. \quad (7)$$

In order to obtain ϑ_i , let $\mathbf{V}_a^{r,i} = [v_{ax}^{r,i}, v_{ay}^{r,i}, v_{az}^{r,i}]^T$ denote the components of $\mathbf{V}_a^b$ in $o^r i x^{r,i} y^{r,i} z^{r,i}$ axes, then $\mathbf{V}_a^{r,i} = [v_{ax}^{r,i}, v_{ay}^{r,i}, v_{az}^{r,i}]^T$ corresponding to rotor 1~4 can be expressed as

$$\begin{aligned} \mathbf{V}_a^{r1} &= \begin{bmatrix} v_{ax}^{r1} \\ v_{ay}^{r1} \\ v_{az}^{r1} \end{bmatrix} = \begin{bmatrix} \cos \varepsilon & 0 & -\sin \varepsilon \\ 0 & 1 & 0 \\ \sin \varepsilon & 0 & \cos \varepsilon \end{bmatrix} \begin{bmatrix} -\sin \xi & \cos \xi & 0 \\ -\cos \xi & -\sin \xi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{ax}^b \\ v_{ay}^b \\ v_{az}^b \end{bmatrix}, \\ \mathbf{V}_a^{r2} &= \begin{bmatrix} v_{ax}^{r2} \\ v_{ay}^{r2} \\ v_{az}^{r2} \end{bmatrix} = \begin{bmatrix} \cos \varepsilon & 0 & -\sin \varepsilon \\ 0 & 1 & 0 \\ \sin \varepsilon & 0 & \cos \varepsilon \end{bmatrix} \begin{bmatrix} \sin \xi & \cos \xi & 0 \\ -\cos \xi & \sin \xi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{ax}^b \\ v_{ay}^b \\ v_{az}^b \end{bmatrix}, \\ \mathbf{V}_a^{r3} &= \begin{bmatrix} v_{ax}^{r3} \\ v_{ay}^{r3} \\ v_{az}^{r3} \end{bmatrix} = \begin{bmatrix} \cos \varepsilon & 0 & -\sin \varepsilon \\ 0 & 1 & 0 \\ \sin \varepsilon & 0 & \cos \varepsilon \end{bmatrix} \begin{bmatrix} \sin \xi & -\cos \xi & 0 \\ \cos \xi & \sin \xi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{ax}^b \\ v_{ay}^b \\ v_{az}^b \end{bmatrix}, \end{aligned}$$

FIGURE 6: The definition of δ_1 .

$$\mathbf{V}_a^{r4} = \begin{bmatrix} v_{ax}^{r4} \\ v_{ay}^{r4} \\ v_{az}^{r4} \end{bmatrix} = \begin{bmatrix} \cos \varepsilon & 0 & -\sin \varepsilon \\ 0 & 1 & 0 \\ \sin \varepsilon & 0 & \cos \varepsilon \end{bmatrix} \begin{bmatrix} -\sin \xi & -\cos \xi & 0 \\ \cos \xi & -\sin \xi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{ax}^b \\ v_{ay}^b \\ v_{az}^b \end{bmatrix}. \quad (8)$$

Then, the angle ϑ_i between the airspeed vector and each rotor plane can be calculated as

$$\vartheta^i = \arccos \frac{\mathbf{V}_a^{ri} \cdot \mathbf{z}^{ri}}{\|\mathbf{V}_a^{ri}\|}, \quad (9)$$

where $\mathbf{z}^{ri} = (0, 0, 1)^T$ is the unit vector.

After ϑ^i is derived, the $\mathbf{F}_{rotor}^{xyz}$ and $\mathbf{M}_{rotor}^{xyz}$ can be obtained by the rotor model. The flight dynamic 6-DoF equation is defined in the body axes, while the $\mathbf{F}_{rotor}^{xyz}$ and $\mathbf{M}_{rotor}^{xyz}$ are defined in the $oxyz$ axes mentioned above, so the $\mathbf{F}_{rotor}^{xyz}$ and $\mathbf{M}_{rotor}^{xyz}$ need to be projected onto the $o^ri x^ri y^ri z^ri$ axes first, then onto the body axes. Thus, the first step is to find the relationship between the $o^ri x^ri y^ri z^ri$ and the $oxyz$ axes. Since the $o^ri x^ri y^ri$ plane and oxy plane are both in the rotor plane, there is only one angle δ_i between the $o^ri x^ri y^ri$ and $oxyz$ axes, as shown in Figure 6, and when ox axis turns clockwise to $o^ri x^ri$ axis, the angle δ_1 is positive.

According to the geometric theory,

$$\sin \delta_1 = \frac{v_{ay}^{r1}}{(v_{ax}^{r1})^2 + (v_{ay}^{r1})^2},$$

$$\cos \delta_1 = \frac{v_{ax}^{r1}}{(v_{ax}^{r1})^2 + (v_{ay}^{r1})^2},$$

$$\sin \delta_2 = \sin (\delta_1 - 2\xi) = \sin \delta_1 \cos (2\xi) - \cos \delta_1 \sin (2\xi),$$

$$\cos \delta_2 = \cos (\delta_1 - 2\xi) = \cos \delta_1 \cos (2\xi) + \sin \delta_1 \sin (2\xi),$$

$$\sin \delta_3 = \sin (\delta_1 + \pi) = -\sin \delta_1,$$

FIGURE 7: The NF-3 wind tunnel in NPU.

FIGURE 8: Wind tunnel test at high sideslip angle.

$$\cos \delta_3 = \cos (\delta_1 + \pi) = -\cos \delta_1,$$

$$\sin \delta_4 = \sin (\pi + \delta_1 - 2\xi) = \cos \delta_1 \sin (2\xi) - \sin \delta_1 \cos (2\xi),$$

$$\cos \delta_4 = \cos (\pi + \delta_1 - 2\xi) = -(\cos \delta_1 \cos (2\xi) + \sin \delta_1 \sin (2\xi)). \quad (10)$$

The forces and moments generated by rotors in the $o^ri x^ri y^ri z^ri$ axes can be calculated by the matrix transformation

$$\begin{bmatrix} x^{ri} \\ y^{ri} \\ z^{ri} \end{bmatrix} = \begin{bmatrix} \cos \delta_i & \sin \delta_i & 0 \\ -\sin \delta_i & \cos \delta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}. \quad (11)$$

FIGURE 9: 9502 dynamic derivative balance.

The next step is to project the forces and moments generated by rotors in the $o^{ri}x^{ri}y^{ri}z^{ri}$ axes onto the body axes. Based on the geometric relationship between the two axes, the force projection $\mathbf{F}_{\text{rotor}}^b = [F_{x,\text{rotor}}^b, F_{y,\text{rotor}}^b, F_{z,\text{rotor}}^b]^T$ can be calculated as

$$F_{x,\text{rotor}}^b = [\cos \varepsilon \sin \xi, \cos \xi, \sin \varepsilon \sin \xi] \begin{bmatrix} -F_x^{r1} + F_x^{r2} + F_x^{r3} - F_x^{r4} \\ -F_y^{r1} - F_y^{r2} + F_y^{r3} + F_y^{r4} \\ -F_z^{r1} + F_z^{r2} + F_z^{r3} - F_z^{r4} \end{bmatrix}, \quad (12)$$

$$F_{y,\text{rotor}}^b = [\cos \varepsilon \cos \xi, \sin \xi, \sin \varepsilon \cos \xi] \begin{bmatrix} F_x^{r1} + F_x^{r2} - F_x^{r3} - F_x^{r4} \\ -F_y^{r1} + F_y^{r2} + F_y^{r3} - F_y^{r4} \\ F_z^{r1} + F_z^{r2} - F_z^{r3} - F_z^{r4} \end{bmatrix}, \quad (13)$$

$$F_{z,\text{rotor}}^b = [\sin \varepsilon, 0, \cos \varepsilon] \begin{bmatrix} -F_x^{r1} - F_x^{r2} - F_x^{r3} - F_x^{r4} \\ 0 \\ F_z^{r1} + F_z^{r2} + F_z^{r3} + F_z^{r4} \end{bmatrix}. \quad (14)$$

The moments generated by rotors $\mathbf{M}_{\text{rotor}}^b = [M_{x,\text{rotor}}^b, M_{y,\text{rotor}}^b, M_{z,\text{rotor}}^b]^T$ can be calculated as

$$M_{x,\text{rotor}}^b = [\cos \varepsilon \sin \xi, \cos \xi, \sin \varepsilon \sin \xi] \cdot \begin{bmatrix} -M_x^{r1} + M_x^{r2} + M_x^{r3} - M_x^{r4} \\ -M_y^{r1} - M_y^{r2} + M_y^{r3} + M_y^{r4} \\ -M_z^{r1} + M_z^{r2} + M_z^{r3} - M_z^{r4} \end{bmatrix} \\ + l_{\text{arm}} \sin \xi [1, 1, -1, -1] \begin{bmatrix} F_z^{r1} \cos \varepsilon - F_x^{r1} \sin \varepsilon \\ F_z^{r2} \cos \varepsilon - F_x^{r2} \sin \varepsilon \\ F_z^{r3} \cos \varepsilon - F_x^{r3} \sin \varepsilon \\ F_z^{r4} \cos \varepsilon - F_x^{r4} \sin \varepsilon \end{bmatrix},$$

$$M_{y,\text{rotor}}^b = [\cos \varepsilon \cos \xi, \sin \xi, \sin \varepsilon \cos \xi] \cdot \begin{bmatrix} M_x^{r1} + M_x^{r2} - M_x^{r3} - M_x^{r4} \\ -M_y^{r1} + M_y^{r2} + M_y^{r3} - M_y^{r4} \\ M_z^{r1} + M_z^{r2} - M_z^{r3} - M_z^{r4} \end{bmatrix} \\ + l_{\text{arm}} \cos \xi [-1, 1, 1, -1] \begin{bmatrix} F_z^{r1} \cos \varepsilon - F_x^{r1} \sin \varepsilon \\ F_z^{r2} \cos \varepsilon - F_x^{r2} \sin \varepsilon \\ F_z^{r3} \cos \varepsilon - F_x^{r3} \sin \varepsilon \\ F_z^{r4} \cos \varepsilon - F_x^{r4} \sin \varepsilon \end{bmatrix}, \\ M_{z,\text{rotor}}^b = [\sin \varepsilon, 0, \cos \varepsilon] \begin{bmatrix} -M_x^{r1} - M_x^{r2} - M_x^{r3} - M_x^{r4} \\ 0 \\ M_z^{r1} + M_z^{r2} + M_z^{r3} + M_z^{r4} \end{bmatrix} \\ + l_{\text{arm}} [1, -1, 1, -1] \begin{bmatrix} F_z^{r1} \sin \varepsilon + F_x^{r1} \cos \varepsilon \\ F_z^{r2} \sin \varepsilon + F_x^{r2} \cos \varepsilon \\ F_z^{r3} \sin \varepsilon + F_x^{r3} \cos \varepsilon \\ F_z^{r4} \sin \varepsilon + F_x^{r4} \cos \varepsilon \end{bmatrix}. \quad (15)$$

The gyroscopic moment of the rotors is defined as

$$\mathbf{M}_{\text{gyro}} = \boldsymbol{\omega}^b \times \mathbf{H}_{\text{rotor}}, \quad (16)$$

where $\mathbf{H}_{\text{rotor}}$ is the angular momentum of the rotor and can be expressed as

$$\mathbf{H}_{\text{rotor}} = J_{\text{rotor}} \boldsymbol{\Omega}_{\text{rotor}}, \quad (17)$$

where $\boldsymbol{\Omega}_{\text{rotor}} = [\Omega_1, \Omega_2, \Omega_3, \Omega_4]^T$ is the rotor speed and J_{rotor} is the moment of inertia about the rotor shaft.

FIGURE 10: Aerodynamic model of the Quad-Plane.

FIGURE 11: Test environment of the rotor and BLDC motor.

The gyroscopic moment of the quadrotor system in body axes is expressed as

$$\mathbf{M}_{\text{gyro}}^{\mathbf{B}} = J_{\text{rotor}} \begin{bmatrix} q \cos \varepsilon (-\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4) + r \sin \varepsilon \cos \xi (\Omega_1 - \Omega_2 - \Omega_3 + \Omega_4) \\ r \sin \varepsilon \sin \xi (\Omega_1 + \Omega_2 - \Omega_3 - \Omega_4) + p \cos \varepsilon (\Omega_1 - \Omega_2 + \Omega_3 - \Omega_4) \\ p \sin \varepsilon \cos \xi (-\Omega_1 + \Omega_2 + \Omega_3 - \Omega_4) + q \sin \varepsilon \cos \xi (-\Omega_1 - \Omega_2 + \Omega_3 + \Omega_4) \end{bmatrix}. \quad (18)$$

FIGURE 12: Test system and data flow.

FIGURE 13: Comparison between the transfer function and the test data of the dynamic characteristics of the electric quadrotor system.

2.4. Wind Disturbance Model. The 1-cos discrete wind model and Von Karman continuous wind model are introduced in this section.

The 1-cos discrete wind model is defined as

$$V_W(t_0, \Delta t) = \begin{cases} 0 & t < t_0, \\ \frac{V_{W \max}}{2} \left(1 - \cos \frac{\pi(t - t_0)}{\Delta t} \right) & t_0 < t < t_0 + \Delta t, \\ V_{W \max} & t_0 + \Delta t < t, \end{cases} \quad (19)$$

FIGURE 14: Comparison between fitted function and test data of power consumption.

where t_0 is the moment when the wind generates, $V_{W \max}$ is the maximum wind speed, and Δt is the time length during which the wind speed changes.

The Von Karman continuous wind disturbance model is introduced in this paper to simulate unsteady wind. The measured wind velocity varies with time is decomposed to two parts:

$$V_W = \overline{V_W} + \Delta V_W, \quad (20)$$

where $\overline{V_W}$ is the mean velocity over a period of time and is defined as

$$\overline{V_W} = \frac{1}{T} \int_0^T V_W(t) dt, \quad (21)$$

FIGURE 15: Position and attitude controller structure of the Quad-Plane, where $\mathbf{X}$ denotes the position or attitude.

FIGURE 16: Target Quad-Plane.

TABLE 1: Parameters of the target Quad-Plane.

Symbol	Explanation	Value
W_{TO} (kg)	Take-off weight	5
I_{xx} (kg·m ²)	Moment of inertia	0.32
I_{yy} (kg·m ²)	Moment of inertia	0.28
I_{zz} (kg·m ²)	Moment of inertia	0.5
I_{xz} (kg·m ²)	Product of inertia	0.017
ξ (°)	Angle between quadrotor arm and $o^b x^b$	45
l_{arm} (m)	Length of arm	0.55
c (m)	Mean aerodynamic chord length	0.3
b (m)	Wing span	2
x_{cg} (m)	Distance in $o^b x^b$ direction from head of fuselage to CG	-0.4015
y_{cg} (m)	Distance in $o^b y^b$ direction from head of fuselage to CG	0

where T is the duration of wind disturbance. ΔV_W is the fluctuating part, the time average of ΔV_W is zero, and the variance of ΔV_W is used to describe the magnitude of the fluctuation and is defined as

$$\sigma_W^2 = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T (\Delta V_W(t))^2 dt. \quad (22)$$

The Von Karman wind turbulence model spectrum function is defined as

$$\Phi_{uu}(\Omega) = \sigma_{u,W}^2 \frac{L_u}{\pi} \frac{1}{[1 + (1.339 L_u \Omega)^2]^{5/6}},$$

$$\Phi_{vv}(\Omega) = \sigma_{v,W}^2 \frac{L_v}{\pi} \frac{1 + 8/3(1.339 \times 2L_v \Omega)^2}{[1 + (1.339 L_v \Omega)^2]^{11/6}},$$

$$\Phi_{ww}(\Omega) = \sigma_{w,W}^2 \frac{L_w}{\pi} \frac{1 + 8/3(1.339 \times 2L_w \Omega)^2}{[1 + (1.339 \times 2L_w \Omega)^2]^{11/6}}, \quad (23)$$

where L_u , L_v , and L_w are turbulence length scale in three directions, $\sigma_{u,W}$, $\sigma_{v,W}$, and $\sigma_{w,W}$ are fluctuation intensity, and they are the function of altitude. For the altitude below 1000 feet, the turbulence length scale and fluctuation intensity are defined as

$$L_w = h,$$

FIGURE 17: The flight simulation architecture.

FIGURE 18: The target Quad-Plane is controlled manually to fly sideward in VTOL mode to generate relative motion between the windless atmosphere and the Quad-Plane.

FIGURE 19: Wind speed measured in flight test, which is used as disturbance wind speed input in simulation.

$$L_u = L_v = \frac{h}{(0.177 + 0.000823h)^{1.2}},$$

$$\sigma_{w,W} = 0.1u_6,$$

$$\sigma_{u,W} = \sigma_{v,W} = \sigma_{w,W} \frac{1}{(0.177 + 0.000823h)^{0.4}}, \quad (24)$$

where h (m/s) is the flight height and u_6 is the wind speed at the height of 6 m.

2.5. Aerodynamic Model. The aerodynamic forces $\mathbf{F}_{aero}$ and moments $\mathbf{M}_{aero}$ acting on the Quad-Plane are both the func-

tion of angle of attack α , sideslip angle β , and airspeed magnitude V_a :

$$\begin{aligned} \mathbf{F}_{aero} &= f(\alpha, \beta, V_a), \\ \mathbf{M}_{aero} &= g(\alpha, \beta, V_a). \end{aligned} \quad (25)$$

When the Quad-Plane works in VTOL mode, based on engineering application, as the roll angle varies in $[-30^\circ, 30^\circ]$, pitch angle varies in $[-30^\circ, 30^\circ]$, and the Quad-Plane will be controllable. So, the ranges of $\alpha \in [-30^\circ, 30^\circ]$ and $\beta \in [0^\circ, 120^\circ]$ are determined in the aerodynamic model, and the surrogate modeling is adopted to establish the high-fidelity model based on sample point data. The data comes

FIGURE 20: Comparison between the Euler angles of Quad-Plane in flight simulation and flight test.

from the results of the wind tunnel test of the Quad-Plane in the NF-3 wind tunnel in Northwestern Polytechnical University, as shown in Figure 7. The wind speed in the test section is set as 11 m/s, corresponding to the wind speed between forces 5 and 6 on the Beaufort scale, and is the wind disturbance rejection performance we expect the Quad-Plane to achieve. The size of the model is the same as that of the real Quad-Plane. The temperature is 8.9°C, the air density is 1.257 kg/m³, and according to the structure of the testbed, the range of sideslip angle varies from 0° to 120° and angle of attack from -25° to 25°, as shown in Figure 8. The 9502 dynamic derivative balance is used to measure the aerodynamic forces and moments acting on the Quad-Plane, as shown in Figure 9. The wind tunnel test data is taken as the sample points, and the Kriging [45] surrogate model is adopted to establish the aerodynamic model of the Quad-Plane, as shown in Figure 10.

2.6. Electric Quadrotor System Model. The electric quadrotor propulsion system consists of the U5-KV400 BLDC motor [46], 16 × 5.4 rotor, and Hobbywing 40A ESC. In order to obtain the dynamic characteristic of the quadrotor system, an experiment is carried out for this set of quadrotor propulsion system. The rotor is fixed on the shaft of the motor, and the motor is fixed on the test bench, as shown in Figure 11. The test system is shown in Figure 12. A Direct Current (DC) power source is used to supply energy, and the ESC is used to drive the BLDC motor. The MINI balance of ATI company is used for thrust and torque measurement. In order to acquire data from the test system, a measurement system using National Instruments (NI) LabVIEW virtual instrumentation is utilized: a CDAQ-9174 device with two compact DAQ modules including NI 9205 and NI 9401. The electric currents of the DC power supply applied to the BLDC motor are also recorded. The second-order transfer function is applied to fit the test data of the dynamic

FIGURE 21: The discrete wind disturbance in flight simulation.

response of the electric quadrotor propulsion system, as shown in Figure 13:

$$G(s) = \frac{29.5}{0.009s^2 + 0.18s + 1}, \quad (26)$$

and the polynomial function is used to fit the test data of the power consumption, as shown in Figure 14:

$$I = 8.46 \times 10^{-11} \text{RPM}^3 + 4.38 \times 10^{-8} \text{RPM}^2 - 5.90 \times 10^{-4} \text{RPM} + 1.57. \quad (27)$$

2.7. Flight Control. In order to make the flight simulation results closer to the real flight data, the flight control algorithm of the Pixhawk Open-source Autopilot, which is equipped on the real Quad-Plane, is adopted in the flight simulation [47], and a double closed-loop PID control scheme is utilized, the structure of the algorithm is shown in Figure 15. The Pixhawk and its autopilot software PX4 are selected for the controller because Pixhawk is widely adopted by academic and developer communities for their

FIGURE 22: The velocity and direction of the wind disturbance.

flexibility and low cost [47]. The outer loop is the position controller, while the inner loop is the attitude controller. The position controller determines the acceleration

$$\begin{aligned}\dot{\Gamma}_d &= k_{p\Gamma}(\Gamma_d - \Gamma), \\ \ddot{\Gamma} &= k_{p\Gamma}(\dot{\Gamma}_d - \dot{\Gamma}) + k_{i\Gamma} \int (\dot{\Gamma}_d - \dot{\Gamma}) dt + k_{d\Gamma} \frac{d(\dot{\Gamma}_d - \dot{\Gamma})}{dt}.\end{aligned}\quad (28)$$

The desired Euler angles are calculated as

$$\begin{aligned}\phi_d &= \arcsin \left(\frac{m\ddot{y}^e \cos \psi - m\ddot{x}^e \sin \psi}{\sqrt{(m\ddot{x}^e)^2 + (m\ddot{y}^e)^2 + (m\ddot{z}^e - mg)^2}} \right), \\ \theta_d &= \arctan \frac{\ddot{x}^e \cos \psi + \ddot{y}^e \sin \psi}{\ddot{z}^e}.\end{aligned}\quad (29)$$

The attitude controller determines the angular acceleration

$$\begin{aligned}\dot{\Theta}_d &= k_{p\Theta}(\Theta_d - \Theta), \\ \ddot{\Theta} &= k_p(\dot{\Theta}_d - \dot{\Theta}) + k_i \int (\dot{\Theta}_d - \dot{\Theta}) dt + k_d \frac{d(\dot{\Theta}_d - \dot{\Theta})}{dt}.\end{aligned}\quad (30)$$

The angular acceleration is calculated as

$$\begin{bmatrix} \ddot{p} \\ \ddot{q} \\ \ddot{r} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin \theta \\ 0 & \cos \phi & \sin \phi \cos \theta \\ 0 & -\sin \phi & \cos \phi \cos \theta \end{bmatrix} \begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix}.\quad (31)$$

Finally, there are four acceleration commands $[\ddot{z}^e, \ddot{p}, \ddot{q}, \ddot{r}]$ which correspond to four basic controllable variables: $U =$

$[U_1, U_2, U_3, U_4]^T$. And the relationship between U and the desired speed of each rotor is calculated as

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} -b & -b & -b & -b \\ -bl \sin \xi & -bl \sin \xi & bl \sin \xi & bl \sin \xi \\ bl \cos \xi & -bl \cos \xi & -bl \cos \xi & bl \cos \xi \\ d & -d & d & -d \end{bmatrix} \begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix}.\quad (32)$$

3. Simulation of the Response Characteristics of the Quad-Plane in VTOL Mode under Wind Disturbance

3.1. Target Quad-Plane. A real Quad-Plane with the take-off weight of 5 kg is taken as an example, as shown in Figure 16. The main parameters of the Quad-Plane are shown in Table 1. The electric quadrotor system consists of four U5-KV400 BLDC motors, four 16×5.4 rotors, four Hobbywing 40A ESCs, and a 6S-10Ah Li-Po battery. The quadrotor mode controller is the Pixhawk with PID technique.

3.2. Flight Simulation Architecture. The entire flight simulation system is composed of several interconnected blocks, as shown in Figure 17. “Inputs” acquire the task commands from the remote controller or the routine programmed in advance, which include the data of the desired position and attitude. These commands are transmitted to the module “position controller” which includes the PID control algorithm for position stabilization, then compares the commands with feedback position to determine the accelerations. Based on the accelerations, the desired Euler angles are solved according to the equation (29) and transmitted to “attitude controller” which includes PID control algorithms and determines the angular acceleration. The “electric quadrotor system” [41] receives the angular accelerations, the vertical acceleration, the velocity and angular rate of the Quad-Plane, and the wind disturbance, then determines the voltage to the motors and outputs the forces and moments

FIGURE 23: The position responses of the Quad-Plane under 1-cos discrete crosswind at different speeds.

FIGURE 24: Rotation speed of each rotor at different disturbance crosswind speeds.

of rotors. These outputs, together with the aerodynamic forces and moments, are inputted to “flight dynamic”—the block which includes the 6-DoF equation of rigid body representing the physics of Quad-Plane and outputs the flight data such as position, velocity, and acceleration in both linear and angular quantities. The block “wind disturbance” includes the 1-cos and Von Karman wind disturbance model, which receives the position of Quad-Plane as input and outputs the velocity vector of wind disturbance. The block “aerodynamic” models the aerodynamic performance of Quad-Plane in the simulation environment, as described in Section 2.5.

The evaluation of the wind disturbance rejection performance depends on (1) the performance to control the position and attitude of the Quad-Plane under a certain intensity of wind disturbance and (2) the power consumption of the Quad-Plane under such wind disturbance.

3.3. Validation. A flight test for acquiring the wind disturbance rejection performance of Quad-Plane in VTOL mode

FIGURE 25: The maximum discrete wind speed that the Quad-Plane can reject at different β_w .

FIGURE 26: Aerodynamic coefficients of the Quad-Plane at different β_w and corresponding maximum discrete wind speed.

is conducted. The test is intended to be carried out by keeping the Quad-Plane hovering in a wind disturbance environment and recording the response of the Quad-Plane. But since it is not easy to find the appropriate wind field to provide disturbance to the Quad-Plane, and because the groundspeed is easier to be recorded, the target Quad-Plane is controlled manually to fly sideward in VTOL mode to generate relative motion between the windless atmosphere and the Quad-Plane, as shown in Figure 18. During the flight test, the propeller equipped behind the fuselage does not work, and the groundspeed shown in Figure 19 is considered identical to the disturbance wind speed because of the windless atmosphere, which is also used as the input in the flight simulation to provide wind disturbance, which guarantees that the wind in simulation and test environment are identical.

The comparison between Euler angles of the flight test and simulation is shown in Figure 20, which shows that the Euler angles obtained from the flight simulation are in good agreement with the test measurement results, and the extremum is slightly greater than that obtained from simulation. The discrepancy between the flight data and simulation results originates from that in actual flight, and the rotating of the rotors makes the flow around the Quad-Plane in actual flight a little different from that in wind tunnel test, so the aerodynamics of the Quad-Plane in actual flight has a little difference from that obtained from the wind tunnel test. According to the comparison between flight simulation and test results, the flight simulation model established can simulate the trend of attitude variation of the Quad-Plane under wind disturbance and has an acceptable high accuracy, which can be used to study the response characteristics of the Quad-Plane under the wind disturbance.

3.4. Response Characteristics in Discrete Wind Disturbance. The 1-cos gust, which is assumed to be parallel to the ground (when the Quad-Plane is subject to the wind disturbance, the direction of the wind disturbance is approximately parallel to the ground in most engineering applications), is intro-

FIGURE 27: Continuous wind disturbances with the same $\overline{V_w} = 5$ m/s and different σ_w .

duced to the simulation. The initial state of the Quad-Plane is $[x^e, y^e, z^e, \psi]_{t=0} = [0, 0, 0, 0]$; as simulation starts, the Quad-Plane is required to take off vertically and rise to 20 meters height and hover. Simultaneously, a discrete wind disturbance is generated and finally ends up at 25 seconds, as shown in Figure 21. The wind speed increases with each simulation, until the Quad-Plane cannot maintain stability anymore. The direction of the discrete wind is denoted as β_w , as shown in Figure 22, when $\beta_w = 90^\circ$ the wind blows from sideward of the Quad-Plane, which is referred to as the crosswind.

The position responses of the Quad-Plane under discrete crosswind disturbance at different speeds are shown in Figure 23. The aerodynamic forces and moments are acting on the Quad-Plane due to the discrete crosswind disturbance, and which makes the position in x^e and y^e deviate from the desired position, the Quad-Plane is then adjusted

FIGURE 28: Position response of Quad-Plane under the Von Karman wind disturbance.

by the flight controller to return to the desired position. As the discrete crosswind speed increases, the deviation of the position increases; finally, as the discrete crosswind speed reaches a certain value, the quadrotor system cannot provide enough control to keep the Quad-Plane stable, and the Quad-Plane crashes.

The response of each rotor at 4.5 m/s, 5.82 ms, and 5.85 m/s discrete crosswind speeds is shown in Figure 24. At the beginning of the simulation, the throttle of each BLDC motor reaches a high value to raise the Quad-Plane. Meanwhile, the discrete crosswind is introduced into the simulation, the aerodynamic forces and moments act on the Quad-Plane, and the Quad-Plane has the trend to be unstable. Then, the flight simulation calculates proper duty cycle for each BLDC motor to control each rotor speed in order to adjust the attitude of the Quad-Plane. In this process, fluctuation of the rotor speed occurs at the beginning of the simulation. As the attitude adjustment completes, the Quad-Plane maintains its position and becomes stable. Subsequently, the discrete crosswind speed keeps constant, so the rotation speed of each rotor remains unchanged. As the simulation goes to 25 seconds, the discrete crosswind ends, and the BLDC motors adjust their rotation speed to identical values. As the discrete crosswind speed increases, the Quad-Plane becomes more uncontrollable and easier to crash. As the discrete crosswind speed reaches 5.85 m/s, the acceleration acting on the Quad-Plane exceeds the limit of the dynamic performance of the quadrotor system, and the Quad-Plane finally crashes, which indicates that the requirement of the dynamic performance of the quadrotor system is higher than that of the steady-state performance.

In reality, the wind disturbance comes from not only sideward. In order to make the Quad-Plane take off and land more safely in the wind disturbance and to design a more antiwind aerodynamic shape, it is necessary to find the direction of the wind disturbance that is the most unfavorable to the Quad-Plane. The variation of the max discrete wind speed the Quad-Plane can reject with different β_w is shown in Figure 25. As $\beta_w = 0^\circ$, the wind comes from the

FIGURE 29: The maximum average continuous wind speed with different fluctuation intensities that the Quad-Plane can reject at different sideslip angles.

head of Quad-Plane, which is the same as the forward flight case in quadrotor mode. As β_w increases, the wind deviates from Quad-Plane's longitudinal symmetry plane, and the discrete wind speed that the Quad-Plane can reject decreases. As β_w increases to 40° , the discrete wind speed decreases to the first minimum, then begins to increase as the β_w continues to increase. As β_w increases to 80° , the discrete wind speed increases to a maximum and then begins to decrease.

Figure 26 shows the corresponding aerodynamic coefficients. The β_w corresponding to the maximum and minimum values of the yawing moment coefficient is the same as the β_w corresponding to the minimum and maximum values of the discrete wind speed. Moreover, the decrease in yawing moment corresponds to the increase in discrete

FIGURE 30: The angular rates of the Quad-Plane with different W_{TO} under 5 m/s crosswind.

wind speed, and the increase in yawing moment corresponds to the decrease in discrete wind speed, which shows that the yawing moment has the greatest correlation with the wind disturbance rejection performance of the Quad-Plane. Secondly, the rolling moment coefficient is also strongly associated with the wind disturbance rejection performance of the Quad-Plane.

3.5. Response Characteristics in Continuous Wind Disturbance. The dynamic response characteristics of the Quad-Plane under continuous wind disturbance are studied. The setup of the flight simulation condition is the same as that in Section 3.4, except the discrete wind is substituted to the continuous wind. The average speed $\bar{V}_W$ is fixed at 5 m/s, different types of continuous wind with different fluctuation intensity σ_W are generated, as shown in Figure 27. The position responses of the Quad-Plane under different continuous wind disturbances are shown in Figure 28. As the continuous wind is unsteady, the position of Quad-Plane also fluctuates with time. With the increase in σ_W , the fluctuation of the position becomes more intense. As the σ_W increases to 0.25 m/s, the Quad-Plane can not maintain the position and crashes.

σ_W

When describing a continuous wind, the average speed is an important parameter. The different continuous winds with different fluctuation intensities may exhibit the same average speed but the impacts of them on the Quad-Plane may be totally different. The variation of the maximum average continuous wind speed with different σ_W that the Quad-Plane can reject at different β_W is shown in Figure 29, the fluctuation intensity σ_W strongly influences the wind disturbance rejection performance of the Quad-Plane. The increase in σ_W degrades the wind disturbance rejection performance, and as β_W increases, the effect of the σ_W becomes more intense. Moreover, the regulation of the wind disturbance rejection performance of the Quad-Plane with different β_W under the continuous wind is similar to that under the discrete wind.

FIGURE 31: The energy consumption of the Quad-Plane with different W_{TO} under 5.6 m/s wind disturbance in 30 s.

FIGURE 32: Crosswind disturbance rejection of the Quad-Plane performance with different W_{TO} .

FIGURE 33: Angular rates of the Quad-Plane with the different moment of inertia under 5 m/s crosswind.

4. Conceptual Layout Parameter Discussion

The factors that influence the wind disturbance rejection performance of the Quad-Plane are as follows:

- (1) The take-off weight W_{TO}
- (2) The moment of inertia, which is related to the mass distribution of the Quad-Plane
- (3) The forces and moments of the rotors, including F_{rotor} , M_{rotor} , and M_{gyro} . According to equations (12)–(18), the effects of the rotors are associated with three main variables: the incline angle of the rotor plane ε , the length of the arm l_{arm} , and the arm angle ξ , both of which are the variables related to the quadrotor system layout
- (4) The aerodynamic forces F_{aero} and moments M_{aero} , which are related to the aerodynamic shape of the Quad-Plane

The influence of factors (1), (2), and (3) on the wind disturbance rejection performance of the Quad-Plane in VTOL mode is studied, providing that the aerodynamic shape of the Quad-Plane, the type of components of quadrotor system, and the control algorithm remain unchanged. According to the above analysis, the above factors can be summarized into three parts related to the conceptual layout: take-off weight, mass distribution, and quadrotor system layout. The discrete crosswind is used as the wind disturbance source because in Section 3.4 and 3.5, it has been indicated that the response characteristics of Quad-Plane under discrete and continuous wind disturbance are consistent. Moreover, it takes much less computational resources to simulate discrete wind disturbance in the simulation program, which is a benefit to the efficiency of the analysis of parameter influence. The simulation time length of each case is set as 30 s because it is the enough time length during which the simulation can get the result that whether a Quad-Plane can reject a wind disturbance with a certain intensity or not.

FIGURE 34: The energy consumption of the Quad-Plane with the different moment of inertia under 5.6 m/s wind disturbance in the 30 s.

FIGURE 35: Crosswind disturbance rejection of the Quad-Plane performance with the different moment of inertias.

4.1. Take-Off Weight. The effect of W_{TO} on the wind disturbance rejection performance in the VTOL model is analyzed. Since the variation of angular rate is more obvious

FIGURE 36: Influence of the CG position on the wind disturbance rejection performance.

FIGURE 37: Influence of the ξ on the wind disturbance rejection performance. FIGURE 38: Influence of the l_{arm} on the wind disturbance rejection performance.

than that of position, the dynamic response of the angular rate with different W_{TO} under 5 m/s wind disturbance is shown in Figure 30. As the W_{TO} increases, the angular rates p , q , and r first decrease and then increase sharply, which indicates that the stability of the Quad-Plane under the wind disturbance first improves and then degrades as the W_{TO} increases.

The energy consumption in 30 s simulation of the Quad-Plane with different W_{TO} under 5 m/s crosswind disturbance is shown in Figure 31, which indicates that the energy consumption increases linearly with the increase in the take-off weight. Meanwhile, the variation of the maximum crosswind speed the Quad-Plane can reject with different take-off weights is plotted in Figure 32, the Quad-Plane shows the best wind disturbance rejection performance with $W_{TO} = 5.1$ kg, and the performance degrades with the W_{TO} deviates from that value. The increase in W_{TO} leads to the decrease in the acceleration of the Quad-Plane under the wind disturbance, which will improve the stability, whereas

FIGURE 39: Max crosswind disturbance rejection performance in different rotor incline angles.

FIGURE 40: Extra moment (in blue) due to rotor incline.

it also impairs the control generated by the quadrotor system, which is not beneficial to the wind disturbance rejection performance. As a result, a Quad-Plane is matched with a certain optimal take-off weight, which makes the Quad-Plane exhibits the best wind disturbance rejection performance, and the W_{TO} deviates from the optimal value will reduce the wind disturbance rejection performance.

4.2. Mass Distribution. The mass distribution affects the moment of inertia and the CG position of the Quad-Plane. The angular rates of Quad-Plane with different moment of inertia under the same wind disturbance are plotted in Figure 33, which shows that with the increase in moment of inertia, the angular rates decrease obviously. Meanwhile, as shown in Figure 34, the energy consumption only increases by 2.79% as the moment of inertia rises by 20%, which brings a lot of benefits to the wind disturbance rejection performance.

The maximum wind disturbance speed of the Quad-Plane with different moment of inertia can reject is plotted in Figure 35. The increase in the moment of inertia reduces the angular acceleration caused by wind disturbance, so the Quad-Plane can reject stronger wind disturbance. As the moment of inertia continues to increase, the control performance of the quadrotor system reduces, so the trend of the increase in wind disturbance rejection performance slows down.

Moreover, the CG position also influences the wind disturbance rejection performance. The primitive CG position is set as $[x_{cg}^b, y_{cg}^b, z_{cg}^b] = [0, 0, 0]$ in body axes, by setting the variation range of the CG position in $x_{cg}^b \in [-0.1c, 0.1c]$ and $z_{cg}^b \in [-0.1c, 0.1c]$, the wind disturbance rejection performance of Quad-Plane with different CG location is simulated, and the results are plotted in Figure 36, which shows that the wind disturbance rejection performance of the Quad-Plane improves as the CG position moves away from the head in longitudinal and upward in vertical, while degrades as the CG position moves towards the head in longitudinal and downward in vertical. Notice that the CG position moves away from the head will decrease the longi-

tudinal static margin as it flies in fixed-wing mode, which decreases the stability in fixed-wing mode flight. Hence, it is hard to both improve the stability of the Quad-Plane in the fixed-wing mode and in the VTOL mode simultaneously by changing the CG position.

4.3. Quadrotor System Layout. The wind disturbance rejection performance of the Quad-Plane with different ξ at different β_W is simulated, and the result is shown in Figure 37. The range of ξ is between 35° and 55° considering the structure constraint. As the ξ increases from 35° , the wind disturbance rejection performance of the Quad-Plane slightly degrades at small β_W while improves at large β_W . Meanwhile, the variation of the wind disturbance rejection performance of the Quad-Plane with different l_{arm} at different β_W is simulated, as shown in Figure 38. The range of l_{arm} is between 0.45 m and 0.65 m, and the wind disturbance rejection performance improves as l_{arm} increases, but the influence is also slight. The maximum wind speed the Quad-Plane can reject increases by less than 8% at the $\beta_W > 10^\circ$ as l_{arm} increases from 0.45 m to 0.65 m, which indicates that the l_{arm} and ξ are not the major influences on the wind disturbance rejection performance.

The influence of ε on the wind disturbance rejection performance of the Quad-Plane is studied by setting different ε in each simulation. Based on the axes defined in Section 2.1, as ε moves positively, the rotor 1 and rotor 4 incline to the head of the Quad-Plane, while the rotor 2 and rotor 3 incline to the rear. The maximum crosswind speed the Quad-Plane can reject with different ε is shown in Figure 39, which shows that the wind speed decreases to the minimum at $\varepsilon = 2.3^\circ$, and the wind speed increases as the ε deviates from that value. Meanwhile, the negatively inclined rotor shows the better wind disturbance rejection performance than the positively inclined rotor with the same absolute magnitude of ε .

The reason can be explained as follows. As the rotor inclines, the rotor axial force F_z^{ri} projects onto $x^b o y^b$ and generates the component denoted as $F_{xy,i}^b$, $F_{xy,i}^b$ multiples l_{arm} generates the moments around $o^b z^b$ axis, which is

FIGURE 41: The energy consumption of the Quad-Plane under 5.6 m/s wind disturbance in 30 s.

FIGURE 42: Wind disturbance rejection performance with different rotor incline angles.

denoted as $M_z^b | F_{xy,i}^b$, as shown in Figure 40. This moment, together with the aerodynamic moment of the rotor around $o^b z^b$ axis $M_{z,i}^b$, will offset the yawing moment acting on the Quad-Plane by wind disturbance. As $\varepsilon < 0$, the $M_z^b | F_{xy,i}^b$ is in the same direction with $M_{z,i}^b$, while as $\varepsilon > 0$, the $M_z^b | F_{xy,i}^b$ is in the opposite direction to $M_{z,i}^b$, as shown in Figure 40; thus, the magnitude of the offset moment in the case $\varepsilon < 0$ is larger than that in the case $\varepsilon > 0$ with the same absolute value of ε . At $\varepsilon = 2.3^\circ$, the magnitude of the offset moment around $o^b z^b$ axis decreases to the minimum, so the wind disturbance rejection performance degrades to the worst. As ε continues to increase, the $M_z^b | F_{xy,i}^b$ increases quicker than $M_{z,i}^b$ so the magnitude of the offset moment around $o^b z^b$ axis increases again, which causes the improvement of wind disturbance rejection performance again.

FIGURE 43: Influence of the l_{arm} on the wind disturbance rejection performance as rotor inclined.

FIGURE 44: Influence of the ξ on the wind disturbance rejection performance as rotor inclined.

The energy consumption of the Quad-Plane at different rotor incline angles under 5.6 m/s wind disturbance in 30 s simulation is shown in Figure 41, which indicates that there exists a rotor incline angle at which the power consumption of Quad-Plane will be the minimum. Meanwhile, there is no data in the middle of the two red curves because the Quad-Plane cannot reject 5.6 m/s wind in such conditions.

The variation of the maximum wind disturbance speeds that the Quad-Plane with different rotor incline angles can reject at different wind directions is plotted in Figure 42, which shows that the change in rotor incline angle is beneficial to the wind disturbance rejection performance in any direction, not only in the crosswind direction.

The effect of the change of the l_{arm} and ξ on the wind disturbance rejection performance of the Quad-Plane becomes much more obvious after the rotor inclines, as shown in Figures 43 and 44. Due to the incline of the rotor, the moment $M_z^b|F_{xy,i}^b$ appears, and the $M_z^b|F_{xy,i}^b$ is amplified with the increase in l_{arm} . Moreover, the increase in ξ benefits the wind disturbance rejection performance at small β_w , and the decrease in ξ benefits the wind disturbance rejection performance at large β_w . The reason is that when β_w is small, the aerodynamic forces and moments acting on the Quad-Plane is mainly longitudinal, and the small ξ makes the quadrotor system produce more longitudinal moments, while when β_w is increasing, the lateral forces and moments gradually dominates, and the larger ξ makes the quadrotor system produce more lateral moments. Based on the above simulation results, the ξ is recommended to be set as 45° to take into account the wind disturbance rejection performance in any direction, and the length of the arm can be increased as possible without affecting the structure.

5. Conclusions

A dynamic simulation system is presented to study the response characteristics of the Quad-Plane in VTOL mode under wind disturbance, which includes high-precision submodules of aerodynamics, rotor, BLDC motor, wind disturbance, and flight control. The results show that the simulation system can obtain the response characteristics of the Quad-Plane under the wind disturbance with high accuracy. The flight stability of Quad-Plane in VTOL mode under wind disturbance is investigated, which shows the following:

- (1) The wind disturbance rejection performance is most associated with the yawing moment acting on the Quad-Plane by the wind disturbance, then with the rolling moment
- (2) The fluctuating intensity of the wind disturbance has more serious influences on the wind disturbance rejection performance than the average speed
- (3) In order to hover in wind disturbance, the quadrotor system requires higher dynamic performance than steady-state performance

The influences of the conceptual layout parameters including take-off weight, mass distribution, and quadrotor system layout on the wind disturbance rejection performance of the Quad-Plane are studied. The results show the following:

- (1) There exists a certain optimum take-off weight to a specific Quad-Plane that will achieve the best wind disturbance rejection performance. If the take-off weight gets higher or lower than the optimum value, the wind disturbance rejection performance will degrade

- (2) Dispersing the mass distribution will improve the wind disturbance rejection performance, which will bring a very small energy consumption increase
- (3) By moving forward and upward the CG position, the wind disturbance rejection performance in VTOL mode will degrade, but the longitudinal stability in fixed-wing mode will improve. It is hard to both improve the disturbance rejection performance in VTOL mode and longitudinal stability in fixed-wing mode by changing the CG position
- (4) It is effective to improve the wind disturbance rejection performance in VTOL mode by inclining the rotor, and there exists a certain incline angle of the rotor, which can minimize the energy consumption
- (5) It is not very useful to improve the wind disturbance rejection performance by changing the arm length and the arm angle on the condition that the rotor does not incline. On the contrary, as the rotor inclines, the increase in arm length brings a lot of benefits to wind disturbance rejection performance. And it is recommended to set the arm angle to 45°

Data Availability

The data can be accessed by sending e-mail to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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