A method for evaluating the wind disturbance rejection capability of a hybrid UAV in the quadrotor mode

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Abstract
The wind disturbance rejection capability of a quadrotor fixed-wing hybrid unmanned aerial vehicle (QFHUAV) in the quadrotor mode is an important factor restricting its large-scale applications. In this paper, based on static equilibrium analysis of the quadrotor mode of a QFHUAV with a wind disturbance, a method for analyzing and evaluating the wind disturbance rejection capability of the QFHUAV in the quadrotor mode is presented. The six degrees-of-freedom (6-DOF) static equilibrium equations of the QFHUAV are established in headwind and crosswind situations. The maximum wind velocity that satisfies the equilibrium equations under the constraints of the maximum thrust and torque of the quadrotor propulsion system is used to determine the wind disturbance rejection capability of the QFHUAV in the quadrotor mode. A QFHUAV with a twin-boom is used as an example to analyze and evaluate its wind disturbance rejection capability in the quadrotor mode. The configuration parameters, quadrotor propulsion system parameters, and aerodynamic parameters affecting the wind disturbance rejection capability of the QFHUAV in the quadrotor mode are presented, discussed, and explained. The yawing moment from the wind disturbance is the main factor threatening the safe flight of the QFHUAV in the quadrotor mode. The rotor disk angle, the maximum thrust of the quadrotor propulsion system, and the moment arms of the components of the quadrotor propulsion system thrust are the main factors affecting the wind disturbance rejection capability of the QFHUAV in the quadrotor mode. Increasing these parameter values is an effective approach to improve the wind disturbance rejection capability of the QFHUAV in the quadrotor mode. From the perspective of wind disturbance rejection capability, tailless and X-type layouts are better choices for QFHUAVs. The correctness of results obtained by the proposed method is verified by two flight test schemes.

Keywords
Wind disturbance rejection capability, quadrotor fixed-wing hybrid unmanned aerial vehicle (QFHUAV), analyze and evaluate, quadrotor mode, maximum wind velocity, factors, improvement approaches

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Introduction
Unmanned aerial vehicles (UAVs) have experienced tremendous development during the last several decades. Currently, UAVs are widely used in various military and civilian applications due to their flexibility in configuration, low manufacturing and operating costs, and not risking pilots in demanding missions, such as surveillance, tracking, environment observation, fish finding, and law enforcement.¹⁻³ Most UAV applications require UAVs that are capable of doing a wide range of different and complementary operations within a composite mission.⁴ However, conventional fixed-wing UAVs generally have good cruise performance, can fly for long durations at high speeds, and are independent of wind situations within a wide range,⁵ but these UAVs suffer from the requirement of runways or special launch and recovery equipment such as catapult launchers, parachutes, or nets for...
takeoff and landing. Rotary wing UAVs, on the other hand, can take off and land vertically. The flight controllers of these UAVs are mature, and these UAVs also do not need any forward airspeed for flight and maneuvering. However, the endurance and operation speed of these UAVs are restricted. As such, a newly emerging and promising trend in UAV design is to design UAVs that join the vertical flight capabilities of rotary wing UAVs with the high-speed, long-duration flight capabilities of fixed-wing UAVs. Inspired by such demands, hybrid UAVs featuring fixed-wings with vertical takeoff and landing (VTOL) capabilities were born.

Studies have been conducted on VTOL UAV concepts including tilt-rotor, tilt-wing, rotor-wing, tail-sitter, and quadrotor fixed-wing hybrid UAV (QFHUAV). Table 1 summarizes the advantages and disadvantages of each of these types of the platforms. The types of platforms that include tilt-rotor, tilt-wing, rotor-wing, and tail-sitter suffer from poor aerodynamic performance, complex control systems and transition maneuvers, unstable vertical flight and susceptibility to disturbances in transitions. As result, large-scale applications of these VTOL UAV concepts are not possible until the technical problems are solved. QFHUAVs utilize a quadrotor propulsion system for vertical flight and a fixed-wing propulsion system for cruise flight. The maturity of the quadrotor and fixed-wing controller ensures the controllability of the QFHUAV along the mission profile. During the transition period, the quadrotor controller maintains stable altitude and attitude, and the fixed-wing controller controls the forward speed to generate lift, and this process ensures that the QFHUAV has smooth transitions. The property of QFHUAVs that pitch angle is maintained around zero along the mission profile increases the flight safety of QFHUAVs and reduces the design requirements. A larger number of commercial off-the-shelf quadrotor and fixed-wing parts give QFHUAVs advantages in manufacturing and maintenance costs. QFHUAVs have no tilting mechanism, have smooth transitions and advantages in control, manufacturing and maintenance costs and are receiving increasing attention.

During the last few years, design methods, controllers and performance of QFHUAVs have been greatly explored. A few successful QFHUAV products, such as the JUMP 15 from Arcturus UAV, the Hybrid Quadcopter from Latitude Engineering, and the CW 007 from JOUAV, have been used in many situations. Both the works in the literature and these products have proven the applicability of QFHUAVs and their potential to be developed.

As shown in Figure 1, in general, the flight profile of a QFHUAV includes VTOL phases, transition phases, and a cruise phase. In the vertical takeoff phase, the quadrotor mode starts and controls the QFHUAV to takeoff vertically at a given climb rate until reaching the given mission altitude. Then, a transition phase begins with the fixed-wing mode starting the pusher motor, giving the QFHUAV a forward speed.

| Type      | Advantages                                                                 | Disadvantages                                                                                           |
|-----------|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| Tilt-rotor| Controllability and stability, simple transition mechanism, efficient forward flight, easy takeoff and landing | Structural complexities, actuators required, poor aerodynamic performance in vertical flight, complex control systems and transition maneuvers |
| Tilt-wing | Simple transition mechanism, good aerodynamic performance                  | Heavy and powerful actuators required, susceptibility to disturbances, complex control systems and transition maneuvers, difficult to land on moving decks |
| Rotor-wing| Lightweight, easy takeoff and landing                                      | Unstable due to single rotor, complex transition mechanism                                              |
| Tail-sitter| No extra actuators, efficient forward flight, various design options for wing geometry, easy takeoff and landing | Unstable vertical flight, complex control systems, susceptibility to disturbances, difficult to land on moving decks |
| QFHUAV    | Maturity of controller, controllability and stability, easy takeoff and landing, various design options for wing geometry | Extra weight, high cruise drag                                                                        |
During this transition period, the QFHUAV gains speed and generates lift, and therefore, the quadrotor controller which is trying to maintain stable altitude and attitude will slow down the rotors. The transition mode can be approximated as the quadrotor mode from the perspective of the attitude control. The cruise phase begins when the QFHUAV reaches the cruise speed and the quadrotor motors shut down completely. For landing, a transition phase begins when the QFHUAV slows down to nearly the stall speed and the quadrotor mode starts again. After enough vertical lift is generated, the pusher motor stops. Then, the landing phase begins.

The applications that arise for QFHUAVs often involve operations in environments that include varied wind conditions. Robustness to external disturbances is crucial for QFHUAVs. The quadrotor propulsion system of a QFHUAV is usually installed symmetrically about the center of gravity (CoG). This system has very little effects on the control and stability of a QFHUAV in fixed-wing mode. The mature control theory and controllers of fixed-wing UAVs can ensure that the QFHUAV in fixed-wing mode flies safely in a wind disturbance situation. However, the quadrotor propulsion system can dramatically increase the drag and slightly reduce the lift when a QFHUAV cruises. A folded quadrotor propeller and folded quadrotor propulsion system support rods have been proposed to minimalize the drag. In research studies, the wind disturbance rejection capability and aerodynamic performance of fixed-wing UAVs are similar to those of manned aircraft, and are not further described in this work. Currently, the majority of QFHUAV controller products and open source autopilots support two high-level control modes, namely Fully Autonomous Control and Semi-Autonomous Control. The Fully Autonomous Control is most commonly used in practical scenario, and this mode automatically attempts to maintain the current location, heading and attitude of a QFHUAV in the quadrotor mode. In this case, the wind disturbance rejection capability of a QFHUAV in the quadrotor mode is approximated as the quadrotor mode from the perspective of the attitude control. The cruise phase of a QFHUAV in fixed-wing mode is proposed to deal with disturbances. The control approach proposed in Alexis et al. is based on linearization and piecewise affine approximations and the controlled output is attitude and not position. Waslander and Wang use wind estimate to improve positioning accuracy by both eliminating the effect of wind on the feedback position control law and adding a wind compensator to mitigate the effect of the expected wind disturbance. The problem of high-precision attitude control for quadrotor UAVs in the presence of wind gusts and actuator faults is addressed in Shi et al. A nonlinear tracking controller with disturbance compensation is proposed based on the estimation of external disturbance forces and torques in Xiao and Yin. Research studies on quadrotor controllers greatly promote the maturity of QFHUAV controllers with wind disturbance rejection. However, the forces and moments from a wind disturbance acting on a QFHUAV in the quadrotor mode are much larger because of the asymmetric configuration and the large windward area, which lead to limited space to improve the wind disturbance rejection capability of the QFHUAV in the quadrotor mode through the controller. Therefore, it is essential to study methods to improve the wind disturbance rejection capability of QFHUAVs in the quadrotor mode through the configuration layout and propulsion system design. Thus far, no literature has been found that studies this issue.

Direct modeling of three-dimensional wind environments is a time-consuming and laborious task in computational fluid dynamics (CFD), for which online solvers that could be incorporated into QFHUAVs do not exist. The difficulty of predicting wind patterns for UAV flight in urban environments is well documented and remains a vibrant area of ongoing research. Both simulation methods by CFD and flight tests in a wind tunnel or wind field are hard to apply in engineering practice at present. However, to improve the wind disturbance rejection capability of a QFHUAV in the quadrotor mode through the configuration layout and propulsion system design, the effects of the wind disturbance on the QFHUAV should be considered in the conceptual design stage, and this approach requires an efficient and accurate method for analyzing and evaluating the wind disturbance rejection capability of QFHUAVs in the quadrotor mode. In particular, the application of multidisciplinary design optimization (MDO) in the conceptual design stage is in need of efficient and accurate wind disturbance rejection capability of QFHUAVs in the quadrotor mode.

A six degrees-of-freedom (6-DOF) static equilibrium analysis of the quadrotor mode of QFHUAVs in wind disturbance situations is introduced in this work. Based on this static equilibrium analysis, an efficient and accurate method for analyzing and evaluating the wind disturbance rejection capability of QFHUAVs in the quadrotor mode is proposed. The factors affecting the wind disturbance rejection capability of QFHUAVs in the quadrotor mode are analyzed using the proposed method. Approaches to improve the wind disturbance rejection capability of QFHUAVs in the quadrotor mode are put forward based on the analysis.
results. The results obtained with the proposed method are validated against two flight tests. The main contributions of this work are listed as follows:

a. A method for analyzing and evaluating the wind disturbance rejection capability of QFHUAVs in the quadrotor mode is proposed. This method provides a numerical method for performance analysis and prediction of QFHUAVs in the design stage.

b. The configuration layout, the rotor disk angle, the maximum thrust of the quadrotor propulsion system, and the moment arms of the components of the thrust of the quadrotor propulsion system are the main factors affecting the wind disturbance rejection capability of QFHUAVs in the quadrotor mode. Both the positive and negative effects of these factors on the wind disturbance rejection capability of QFHUAVs in the quadrotor mode are analyzed. Approaches to improve the wind disturbance rejection capability of QFHUAVs in the quadrotor mode are also provided.

The rest of this paper is organized as follows. The static equilibrium analysis of QFHUAVs in the quadrotor mode and the wind disturbance model are described in the next section. Then, a method for analyzing and evaluating the wind disturbance rejection capability of QFHUAVs in the quadrotor mode is presented. Subsequently, the parameters of a QFHUAV that is used as a test case example are introduced. The wind disturbance rejection capability of QFHUAVs in the quadrotor mode, the factors affecting the wind disturbance rejection capability of QFHUAVs in the quadrotor mode and improvement approaches are presented. Two flight tests are demonstrated. Finally, conclusions are given.

Static equilibrium analysis of the quadrotor mode in a wind disturbance situation

Static equilibrium analysis of the quadrotor mode

The QFHUAV is modeled as a rigid body. The coordinate frames and reference vectors for the problem of interest are defined in Figure 2(a), including the Earth-fixed inertial coordinate frame I (O_I X_I Y_I Z_I), and the body coordinate frame B (O_B X_B Y_B Z_B) with the origin O_B as the CoG. The Euler angles \( \Theta = [\phi, \theta, \psi]^T \) are adopted to represent the attitude angles of frame B with respect to frame I, where \( \phi \) is the roll angle, \( \theta \) is the pitch angle and \( \psi \) is the yaw angle. The thrust and torque considered for each rotor system are visible for each rotor \((T_k, Q_k)\) and expressed in frame B, with rotor 1 rotating clockwise on the front right of the body, rotor 2 rotating counterclockwise on the front left of the body, etc. Rotor 1/rotor 2 and rotor 3/rotor 4 are symmetric about the \( O_B Y_B Z_B \) plane. Rotor 1/rotor 4 and rotor 2/rotor 3 are symmetric about the \( O_B X_B Z_B \) plane. The wind velocity \( v_w \) is also depicted and is expressed in frame I, where \( \beta \) is the angle between the opposite direction of \( v_w \) and the \( O_I X_I \) axis.

The installation of the rotors is presented in Figure 2(b) and labeled only for rotor 4 to avoid unnecessary clutter. In practice, the thrust generated by this rotor \( T_{4R} \) is perpendicular to the rotor disk plane and not to the hub of the rotor. In this work, the tilt of the rotor thrust is ignored to simplify the analysis method of the wind disturbance rejection capability of QFHUAVs in the quadrotor mode. The analysis in the section Quadrotor propulsion system indicates that it is reasonable to assume that the thrust of the rotor is perpendicular to the hub of the rotor.

As shown in Figure 2(b), based on the above simplification, \( T_4 \) is the thrust of rotor 4, and this thrust is perpendicular to the hub of the rotor and coincides with the motor shaft. \( \delta \) is the angle between the direction of \( T_4 \) and the opposite direction of the \( O_B Z_B \) axis, and this angle is usually called the rotor disk angle. \( \epsilon \) is the angle between the projection of \( T_4 \) on the \( O_B Y_B Z_B \) plane and the opposite direction of the \( O_B Z_B \) axis. \( \zeta \) is the angle between the projection of \( T_4 \) on the \( O_B X_B Z_B \) plane and the opposite direction of the \( O_B Z_B \) axis. \( \sigma \) is the angle between the projection of \( T_4 \) on the \( O_B X_B Y_B \) plane and the opposite direction of...
of the $O_BX_B$ axis. Because the motor shaft is usually perpendicular to the diagonal of the quadrotor motor position, $\sigma$ is also equal to the angle between the diagonal of the quadrotor motor position and the $O_BY_B$ axis. $T_{x4}$, $T_{y4}$, and $T_{z4}$ are the components of thrust $T_4$ on the $O_BX_B$, $O_BY_B$ axis and $O_BZ_B$ axis, respectively. $d_1$ and $d_2$ are the distances between the installation position of the rotor disks and the $O_BX_B$, $O_BY_B$ and $O_BZ_B$ axis, respectively. $Z_g$ is the vertical distance from the center of the rotor disk to the position of the CoG. Figure 2(b) also shows the forces and moments from the wind disturbance ($L_w$, $D_w$, $Y_w$, $M_w$, $M_x$, and $M_z$) and the gravitational force ($mg$) acting on the vehicle, where $m$ is the total mass of the QFHUAV, and $g$ is the gravitational acceleration.

Let $X = [x, y, z]^T$ be the position of the CoG with respect to frame I and expressed in frame I. The rotation matrix for rotation from frame B to frame I is denoted as $R(\Theta)$ and expressed as

$$R(\Theta) = \begin{bmatrix} C\Theta C\Psi & S\Theta S\Psi & -S\Psi C\Psi \\ C\Theta S\Psi & S\Theta C\Psi & S\Psi C\Theta \\ -S\Theta & S\Theta & C\Theta \end{bmatrix}$$

where the terms $S_\cdot$ and $C_\cdot$ denote the trigonometric functions $\sin(\cdot)$ and $\cos(\cdot)$, respectively.

At steady state, the combination of forces and moments acting on the vehicle in the quadrotor mode results in the following static equilibrium equations that are expressed in frame B

$$R(\Theta)^T(f + d + mg e_z) = 0$$

$$\tau + \tau_d = 0$$

where $e_z = [0, 0, 1]^T$, $f$ is the total thrust of the quadrotor propulsion system in frame I as follows

$$f = R(\Theta) \begin{bmatrix} T_{x1} + T_{x2} - T_{x3} - T_{x4} \\ -T_{y1} + T_{y2} + T_{y3} - T_{y4} \\ -(T_{z1} + T_{z2} + T_{z3} + T_{z4}) \end{bmatrix}$$

where $T_{xk}$, $T_{yk}$, and $T_{zk}$ ($k = 1, 2, 3, 4$) are expressed in frame B and given as

$$[T_{xk} \ T_{yk} \ T_{zk}]^T = [T_k \sin \delta \cos \sigma \ T_k \sin \delta \sin \sigma \ T_k \cos \delta]^T$$

$d$ denotes the disturbance forces acting on the vehicle and is expressed in frame I as follows

$$d = [-D_w \ Y_w \ -L_w]^T$$

$\tau$ is the total control moment for rotational motion and is expressed in frame B as follows

$$\tau = \begin{bmatrix} Q_{x11} + T_{y11}d_1 + T_{y12}d_2 + T_{y13}Z_g \\ Q_{x21} + T_{y21}d_1 + T_{y22}d_2 + T_{y23}Z_g \\ Q_{x31} + T_{y31}d_1 + T_{y32}d_2 + T_{y33}d_3 \end{bmatrix}$$

where

$$Q_{x11} = Q_{x1} - Q_{x2} - Q_{x3} + Q_{x4}$$

$$Q_{x21} = -Q_{y1} - Q_{y2} + Q_{y3} + Q_{y4}$$

$$Q_{x31} = -Q_{z1} + Q_{z2} - Q_{z3} + Q_{z4}$$

$$T_{x1} = -T_{x1} + T_{x2} + T_{x3} - T_{x4}$$

$$T_{y1} = -T_{y1} + T_{y2} - T_{y3} + T_{y4}$$

$$T_{z1} = -T_{z1} + T_{z2} + T_{z3} - T_{z4}$$

$$T_{x2} = -T_{x1} - T_{x2} + T_{x3} + T_{x4}$$

$$T_{y2} = -T_{y1} - T_{y2} - T_{y3} + T_{y4}$$

$$T_{z2} = -T_{z1} - T_{z2} - T_{z3} + T_{z4}$$

and $\tau_d$ denotes the disturbance moments acting on the QFHUAV and is expressed in frame B as follows

$$\tau_d = [M_x \ M_y \ M_z]^T$$

The forces and moments from the wind disturbance are functions of the lift coefficient $C_L$, drag coefficient $C_D$, side-force coefficient $C_Y$, rolling moment coefficient $C_b$, pitching moment coefficient $C_m$, and yawing moment coefficient $C_n$ as follows

$$[D_w \ Y_w \ L_w \ M_x \ M_y \ M_z]^T = \rho \frac{v_w^2 S_{ref}}{2} \begin{bmatrix} C_D & C_Y & C_L & C_b & C_m & C_n \end{bmatrix}^T$$

where $\rho$ is the atmospheric density, $S_{ref}$ is the wing reference area, $b$ is the wing span, and $c$ is the wing mean geometric chord.
The thrust and torque of the quadrotor motor-rotor system are proportional to the rotational speed square \( \omega^2 \), which is expressed as follows

\[
T_k = k_T(J)\omega^2, \quad Q_k = k_Q(J)\omega^2, \quad J = \frac{60v_{tk}}{\omega D_p} \tag{20}
\]

where \( k_T \) and \( k_Q \) are functions of the advance ratio \( J \), which is a function of the incoming axial speed \( v_{tk} \), the rotational speed \( \omega \) in revolutions per minute and the rotor diameter \( D_p \).

**Wind disturbance modeling**

Because short-term, turbulent wind effects are difficult to model even with detailed CFD analysis, assumptions such as constant wind fields are often used.\(^\text{24}\) For a QFHUAV, the energy consumption of the quadrotor power system is much greater than the energy consumption of the fixed-wing power system during the same time period. Thus, the working time of the quadrotor mode should be as short as possible to save energy. In a practical scenario, the takeoff and landing time is usually within a few minutes, during which the wind patterns do not change significantly. Therefore, in this work, the wind is assumed to be two-dimensional with constant velocity as follows

\[
v_w = [v_w \cos \beta \ v_w \sin \beta \ 0]^T \tag{21}
\]

**A method for analyzing and evaluating the wind disturbance rejection capability**

The wind disturbance rejection capability of a QFHUAV in the quadrotor mode is equivalent to whether the quadrotor propulsion system of the QFHUAV can balance the forces and torques from wind disturbances. The static equilibrium state of a QFHUAV in a wind disturbance situation can be used to indicate that the QFHUAV can resist the wind. Then, the force and torque equilibrium equations of the QFHUAV can be established. The maximum wind velocity that satisfies the equilibrium equations under the constraints of the maximum thrust and torque of the quadrotor propulsion system can be used to measure the wind disturbance rejection capability of the QFHUAV in the quadrotor mode. The higher the maximum wind velocity is, the stronger the wind disturbance rejection capability. From the above analysis, the 6-DOF static equilibrium equations can be used to quantify the wind disturbance rejection capability of the QFHUAV in the quadrotor mode approximately, and these static equilibrium equations can be established according to equations (2) and (3).

To ensure safe takeoff and landing in high wind speed conditions, operators usually forecast the wind direction in mission planning and path planning to keep the angle between the heading of a QFHUAV and the negative direction of the wind as small as possible. These operations ensure that the angle between the negative direction of the wind and the heading of the QFHUAV is between \(-90^\circ\) and \(90^\circ\). Based on the wind disturbance model and engineering practice, the wind direction can be decomposed into two parts due to the symmetry of the QFHUAV configuration. One part is opposite to the heading of the QFHUAV and the other is perpendicular to the plane of symmetry, these parts are called headwind and crosswind, respectively. Then, the wind disturbance rejection capability of the QFHUAV in the quadrotor mode can be analyzed and evaluated independently in these headwind and crosswind situations.

**Headwind situation**

In the headwind situation, the wind velocity is expressed in frame \( I \) as follows

\[
v_w = [v_{w} \ 0 \ 0]^T \tag{22}
\]

In this situation, the side force, rolling moment and yawing moment can be neglected due to the symmetry of the configuration as follows

\[
Y_w = M_x = M_z = 0 \tag{23}
\]

Figure 3 illustrates the forces and moments acting on the QFHUAV and the attitude of the QFHUAV in this situation. \( \theta \) is the pitch angle at which the QFHUAV remains stable. \( v_{tm} \) (\( m = 1, 2 \)) and \( v_{tn} \) (\( n = 3, 4 \)) are the axial flow velocities of rotors 1, 2 and 3, 4, respectively, that are the components of the wind velocity \( v_w \).

![Figure 3. The forces, moments and attitude in the headwind situation.](image-url)
The gravitational and aerodynamic forces are projected onto frame $B$ by the following equations for convenience

$$
\begin{bmatrix}
G_x & G_y & G_z
\end{bmatrix}^T = R(\Theta, \psi = \varphi = 0)^T \begin{bmatrix}
0 & 0 & mg
\end{bmatrix}^T
$$

(24)

$$
\begin{bmatrix}
F_x & F_y & F_z
\end{bmatrix}^T = R(\Theta, \psi = \varphi = 0)^T \begin{bmatrix}
-D_w & Y_w & -L_w
\end{bmatrix}^T
$$

(25)

A QFHUAV can resist the wind disturbance if the forces and moments acting on the QFHUAV are in equilibrium when it hovers in the headwind situation. According to equations (2) and (3), the following equations must be satisfied

$$
-T_{ztot} + G_z + F_z = 0
$$

(26)

$$
-T_{x21} + G_x + F_x = 0
$$

(27)

$$
T_{z21}d_2 + T_{x21}Z_g + Q_{y21} + M_y = 0
$$

(28)

where

$$
T_{ztot} = T_{z1} + T_{z2} + T_{z3} + T_{z4}
$$

(29)

According to equation (20), the thrust and torque of the quadrotor propulsion system ($T_k, Q_k$) vary with the axial wind velocity of the rotors for a given rotational speed. $T_k$ and $Q_k$ should not be larger than their maximum values ($T_{max}, Q_{max}$). Their relationships and constraints are expressed as follows

$$
T_k \leq T_{max}, \quad Q_k \leq Q_{max}
$$

(30)

As shown in Figure 3, the angles between the wind direction and the rotor disks numbered 1 and 2 are ($\zeta + \theta$), and the angles between the wind direction and the rotor disks numbered 3 and 4 can be approximated to ($|\zeta - \theta|$). When $\zeta \geq \theta$, since $|\zeta - \theta|$ decreases with increasing $\theta$, $v_{in}$ ($n = 3, 4$) is small enough to be neglected in this situation. Then, the axial flow velocities of the rotors $v_{tk}$ ($k = 1, 2, 3, 4$) can be obtained as follows

$$
v_{t1} = v_{t2} = v_w \sin(\zeta + \theta)
$$

(32)

$$
v_{t3} = \begin{cases} 
v_w \sin(\theta - \zeta) & 0 \leq \theta \\
v_w & \theta > \zeta
\end{cases}
$$

(33)

where $\zeta$ satisfies the following equation according to the geometrical relationship shown in Figure 2(b)

$$
\tan \zeta = \cos \delta \tan \varphi
$$

(34)

**Crosswind situation**

In the crosswind situation, the wind velocity is expressed in frame $I$ as follows

$$
v_w = \begin{bmatrix} 0 & v_w & 0 \end{bmatrix}^T
$$

(35)

A QFHUAV that is hovering in the crosswind situation is illustrated in Figure 4. The Euler angles $\Theta = [\varphi, \theta, \psi]^T$ are used to represent the attitude intuitively. In this situation, $v_{ti}$ ($i = 2, 3$) and $v_{tj}$ ($j = 1, 4$) are the

$$
T_{\max} = f_1(v_{tk}, \omega_{max}), \quad Q_{\max} = f_2(v_{tk}, \omega_{max})
$$

(31)

**Figure 4.** The forces, moments and attitude of a QFHUAV in the crosswind situation.
axial flow velocities of rotors 2, 3 and 1, 4, respectively, that are the components of the wind velocity $v_w$ in the $O_9 Y_9 Z_9$ plane.

The gravitational and aerodynamic forces are projected onto frame $B$ by the following equations for convenience

$$
\begin{bmatrix}
G_x & G_y & G_z
\end{bmatrix} = R(\Theta)^T \begin{bmatrix} 0 & 0 & mg \end{bmatrix}^T \tag{36}
$$

$$
\begin{bmatrix}
F_x & F_y & F_z
\end{bmatrix} = R(\Theta)^T \begin{bmatrix} -D_w & Y_w & -L_w \end{bmatrix}^T \tag{37}
$$

To specify the parameters that affect the wind disturbance rejection capability of a QFHUAV in the quadrotor mode, a matrix $H$ is used to represent the parameters affecting the wind disturbance rejection capability of the QFHUAV in the quadrotor mode intuitively, and the matrix is given by

$$
H = \begin{bmatrix}
-T_{c11} & 0 & G_x & F_x \\
T_{r11} & 0 & G_y & F_y \\
T_{z10} & 0 & G_z & F_z \\
T_{z11} & T_{r11} & Q_{c11} & M_x \\
T_{z21} & T_{r21} & Q_{c21} & M_y \\
T_{z31} & T_{r31} & Q_{c31} & M_z \\
\end{bmatrix} \begin{bmatrix}
1 & 1 & -1 & d_1 & d_2 & d_3 \\
0 & 0 & 0 & Z_d & Z_g & d_1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 \\
\end{bmatrix}
$$

$$
H(1,1) H(2,2) H(3,3) H(4,4) H(5,5) H(6,6) \Rightarrow 0
$$

According to equations (2) and (3), equation (39) must be satisfied when the QFHUAV can resist the wind disturbance. The thrust and torque of the quadrotor propulsion system ($T_b, Q_b$) and their maximum values ($T_{max}, Q_{max}$) should also satisfy equations (30) and (31). $v_{w1}$ and $v_{w2}$ are used to analyze the effects of the wind velocity on the thrusts and torques of the rotors. As shown in Figure 4, the angles between the wind direction and the rotor disks numbered 2 and 3 can be approximated to $(\varepsilon + \varphi)$, and the angles between the wind direction and the rotors disks numbered 1 and 4 can be approximated to $(|\varepsilon - \varphi|)$. When $\varepsilon \geq \varphi$, since $|\varepsilon - \varphi|$ decreases with increasing $\varphi$, $v_{w1} (j = 1, 4)$ is small enough to be neglected. Then, the axial flow velocities of the rotors $v_{wh} (k = 1, 2, 3, 4)$ can be obtained as follows

$$
v_{z2} = v_{z3} = v_w \sin(\varepsilon + \varphi) \tag{40}
$$

$$
v_{z1} = v_{z4} = \begin{cases} 
0 & \varepsilon \geq \varphi \\
v_w \sin(\varphi - \varepsilon) & \varepsilon < \varphi 
\end{cases} \tag{41}
$$

where $\varepsilon$ satisfies the following equation according to the geometrical relationship shown in Figure 2(b)

$$
tan\varepsilon = \sin\delta \tan\delta \tag{42}
$$

Parameters of a QFHUAV

Conceptual parameters

A QFHUAV with a twin-boom is used as an example to analyze and evaluate its wind disturbance rejection capability in the quadrotor mode. Both the quadrotor mode and the fixed-wing mode of the QFHUAV maintain a level fuselage when it flies in a windless situation. A diagram of the QFHUAV is shown in Figure 2(a). The conceptual parameters of the QFHUAV are presented in Table 2.

Aerodynamic performance

The aerodynamic coefficients of the QFHUAV are simulated using commercial CFD solver ANSYS CFX. The numerical parameters are applied as follows: The option of the Analysis Type is Steady State. In Default Domain Modified, the material of the Fluid Model is Air Ideal Gas, which is compressible. The option of the Morphology is Continuous Fluid. The option of Turbulence is Shear-Stress Transport model with automatic Wall Function. The option of the Heat Transfer is Total Energy. In Solver Control, both the options of Advection Scheme and Turbulence Numerics are High Resolution. The Maximum Iterations is set to 200 and the Timescale Factor is set to 1. The Residual Target is set to $1e-6$. The atmospheric pressure and temperature are set to 0.93 atm and 284.25 K, respectively, which give atmospheric density and dynamic viscosity equal to 1.185 kg/m$^3$ and 1.831 $\times 10^{-5}$ Pa-s, respectively. An unstructured grid with 14 million cells is used in the model.

The lift coefficient $C_L$, drag coefficient $C_D$, and pitching moment coefficient $C_m$ simulated in the headwind situation are shown in Figure 5. In the crosswind situation, the aerodynamic coefficients of the QFHUAV are

| Symbol | Quantity | Value |
|--------|----------|-------|
| $S_{ref}$ | wing reference area | 1.6 m$^2$ |
| $b$ | wing span | 3.8 m |
| $c$ | wing mean geometric chord | 0.425 m |
| $m$ | takeoff weight | 30 kg |
| $\alpha$ | wing incidence angle | $3^{\circ}$ |
| $\delta$ | rotor disk angle | $0^{\circ}$ |
| $\sigma$ | angle between the diagonal of the quadrotor motor position and the $O_9 Y_9$ axis | $45^{\circ}$ |
| $d_1$ | distance between the installation position of the rotor disks and the $O_9 X_9$ axis | 0.7 m |
| $d_2$ | distance between the installation position of the rotor disks and the $O_9 Y_9$ axis | 0.7 m |
| $Z_d$ | vertical distance from the center of the rotor disk to the position of the CoG | 0.18 m |
simulated with a pitch angle in the range of $-20^\circ$ to $20^\circ$, a roll angle in the range of $-30^\circ$ to $30^\circ$, and a yaw angle in the range of $-30^\circ$ to $30^\circ$. The CFD method is very time consuming. Therefore, the interval between the values of each Euler angle is $10^\circ$. Because of the four dimensions, it is difficult to graph the results that consist of the lift coefficient $C_L$, drag coefficient $C_D$, side force coefficient $C_Y$, rolling moment coefficient $C_\alpha$, pitching moment coefficient $C_m$, and yawing moment coefficient $C_n$.

Surrogate models are based on statistical theory techniques, consider good fitting accuracy and test performance as the goal, adopt mathematical approximation techniques for discrete sample data to build regression analysis or mathematical interpolation models, construct approximate mathematical models to predict the unknown variable space by the limited known sample point and its corresponding response, and obtain the trend of output variables with design variables. With the development of approximation techniques, surrogate models could gradually replace highly accurate CFD analysis, guarantee the fitting precision and reduce design costs in engineering design.\textsuperscript{28}

Surrogate models involve (a) choosing an experimental design for generating sample points, (b) choosing a model to represent the sample points, and (c) fitting the model to the observed data.\textsuperscript{29} The elliptical basis function neural network (EBF-NN) model is a common surrogate model and is composed of an input layer, a hidden layer of elliptical units and an output layer of linear units. This model is useful in approximating a wide range of nonlinear spaces.\textsuperscript{28} In this work, the EBF-NN model is used to approximate the relationships between the Euler angles and the aerodynamic coefficients.

### Quadrotor propulsion system

A carbon fiber propeller with two blades is chosen as the rotor of the quadrotor propulsion system. The diameter and pitch of the propeller are 30 in $\times$ 9.5 in, respectively, and the cross sections of the blade belong to the GOE airfoils. An off-the-shelf brushless direct current electric (BDCE) motor with speed constant $KV = 115$ is selected to drive the rotor.

The aerodynamic coefficients of the rotor are simulated using commercial CFD solver ANSYS CFX. The computational domain is shown in Figure 6. The numerical parameters are applied as follows: The material of the fluid model is Air Ideal Gas, which is compressible. The maximum iterations is set to 2000 and the Timescale Factor is set to 15. The other numerical parameters applied in CFX are the same as those in the previous section except for the option of the Analysis Type.

1. **Aerodynamic performance of the rotor with axial flow.** The multiple reference frame (MRF) model is used to simulate the aerodynamic performance of the rotor with axial flow. The option of the Analysis Type in CFX is set to Steady State. The actual maximum rotational speed of the motor-rotor system is approximately 4000 r/min. The effects of the axial flow velocity $v_{ik}$ on the thrust and torque of the rotor ($T_k$, $Q_k$) are shown in Figure 7.

2. **Aerodynamic performance of the rotor with oblique flow.** The sliding mesh method is employed to simulate the unsteady aerodynamic forces of the rotor with oblique flow.

![Figure 5. The aerodynamic coefficients in the headwind situation.](image)

| Dependent variable | $C_L$ | $C_D$ | $C_Y$ | $C_\alpha$ | $C_m$ | $C_n$ |
|-------------------|------|------|------|------------|------|------|
| $R^2$             | 0.997| 0.984| 0.970| 0.996      | 0.995| 0.981|

![Figure 6. The computational domain.](image)
flow. In CFX, the option of the Analysis Type is set to Transient. The Total Time of the Time Duration is set to 1 s and the Timesteps of the Time Steps is set to 0.01 s.

As shown in Figure 8, \( \alpha \) is the rotation axis of the rotor that coincides with the motor shaft, the \( oyz \) plane is the rotor disk plane, \( v_w \) is the freestream speed, \( \gamma \) is the angle formed by the rotation axis and the freestream direction, \( \Phi_p \) is the azimuth angle of the rotor blade, and \( \omega \) is the rotational speed. The forces and moments in all three directions of the rotor are simulated in a particular working condition with freestream speed \( v_w = 15 \text{ m/s} \), the theoretical maximum rotational speed of the rotor \( \omega = 4300 \text{ r/min} \) and \( \gamma = 35^\circ \). The results for one cycle of the rotor are shown in Figure 9, where \( F_{xp}, F_{yp}, \) and \( F_{zp} \) are the forces exerted on the rotor and \( M_{xp}, M_{yp}, \) and \( M_{zp} \) are the moments exerted on the rotor. Table 4 shows the averages and extremes of the forces and the moments.

The carbon fiber material of the rotor is T300/5208, which has high stiffness and the blade-flapping effects of the rotor can be neglected. As shown in Figure 10, the angle formed by the rotation axis and resulting force \( F_r \) can be obtained as

\[
\delta_{pr} = \arccos \left( \frac{F_{xp}}{\sqrt{F_{xp}^2 + F_{yp}^2 + F_{zp}^2}} \right) \approx 1.6^\circ \tag{43}
\]
The wind velocity and rotor rotational speed in most of the application environments of QFHUAVs are no more than 15 m/s and 4300 r/min, respectively. From the above analysis, the maximum of the angle formed by the rotation axis and resulting force is less than $2/C_{14}$ in most of the application environments of QFHUAVs. This small value of $\delta_{pa}$ has no effects on the trends of the analysis results of the wind disturbance rejection capability of QFHUAVs in the quadrotor mode.

In addition, the simulation of the aerodynamic performance of the rotor with oblique flow is a time-consuming and laborious task. Therefore, it is reasonable to assume that the resulting thrust of the rotor is always perpendicular to the hub of the rotor.

### Results and discussion

#### The wind disturbance rejection capability of the QFHUAV in the quadrotor mode

The wind disturbance rejection capability in the headwind situation. As shown in Figure 11, the aerodynamic coefficients in Figure 5 and the quadrotor propulsion system parameters of the example QFHUAV can be substituted into equations (26) to (28) to obtain the relationship between the pitch angle $\theta$ and the maximum wind velocity $v_{w_{\text{max}}}$ that the QFHUAV can resist. The maximum headwind velocity that the QFHUAV can resist is 16 m/s, which indicates that the wind disturbance rejection capability of the QFHUAV is strong. The forces and moments from the wind disturbance acting on the QFHUAV are easily balanced due to the symmetry of the configuration, and this effect accounts for the wind disturbance rejection capability.

The relationships between the thrust of each quadrotor motor-rotor system $T_k$, the total thrust of the quadrotor propulsion system $T_{\text{tot}}$ and the wind velocity $v_w$ are presented in Figure 12. $T_k$ and $T_{\text{tot}}$ decrease with increasing wind velocity in the range of 0 to 9 m/s and then increase as the wind velocity increases further. As shown in Figure 11, the pitch angle is larger than $-3^\circ$ when the wind velocity is less than 9 m/s. Figure 5 shows that the zero-lift angle of the QFHUAV is approximately $-6^\circ$. When the pitch angle decreases in the range of $-3^\circ$ to $0^\circ$, the lift coefficient of the QFHUAV $C_L$ is positive and decreases linearly, the drag coefficient $C_D$ decreases slightly, and the pitching moment coefficient $C_m$ increases slightly, and the value is nearly 0. The decrease in the lift coefficient $C_L$ with decreasing pitch angle is less than the increase in $v_w^2$. According to equation (19), when the wind velocity increases in the range of 0 to 9 m/s, the lift $L_w$ is positive and increases gradually, the changes in the drag $D_w$ are small, and the pitching moment $M_y$ is nearly 0. Therefore, a positive and increasing lift reduces the

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**Table 4.** The averages and extremes of the forces exerted on the rotor.

| Items          | Average | Max. | Azimuth angle of maximum | Min. | Azimuth angle of minimum |
|----------------|---------|------|--------------------------|------|--------------------------|
| $F_{xp}/N$     | -136.9  | -132.5 | 305°                     | -140.4 | 50°                      |
| $F_{yp}/N$     | 4.0     | 8.6   | 175°                     | -0.49 | 85°                      |
| $F_{zp}/N$     | 0.74    | 5.14  | 40°                      | -3.65 | 130°                     |
| $M_{xp}/N\cdot m$ | -5.14  | -5.03 | 100°                     | -5.27 | 0°                       |
| $M_{yp}/N\cdot m$ | -5.24  | 0.88  | 105°                     | -11.55 | 15°                      |
| $M_{zp}/N\cdot m$ | -2.78  | 3.12  | 330°                     | -8.73 | 55°                      |

---

**Figure 10.** A sketch diagram of the thrust of the rotor with oblique flow.

**Figure 11.** The maximum wind velocity versus pitch angle.
required thrust of the QFHUAV. This effect is the main reason why \( T_k \) and \( T_{tot} \) decrease with increasing wind velocity in the range of 0 to 9 m/s. When the wind velocity is larger than 9 m/s, the absolute values of the drag and pitching moment increase, and the lift is positive but decreases rapidly with decreasing pitch angle in the range of \(-6^\circ\) to \(-3^\circ\). The lift decreases further and becomes negative when the pitch angle is less than \(-6^\circ\). For this reason, the required thrust of the quadrotor propulsion system increases with increasing wind velocity, and the rate of increase of the required thrust increases gradually. The results in Figure 12 indicate that a low-speed headwind can be used to reduce the power consumption of the quadrotor propulsion system.

The wind disturbance rejection capability in the crosswind situation. The aerodynamic coefficients approximated using the EBF-NN model and the quadrotor propulsion system parameters shown in Figure 7 can be substituted into equation (39) to obtain the relationship between the Euler angles \( \Theta = [\phi, \theta, \psi]^T \) and the maximum wind velocity \( v_{w\text{max}} \) that the QFHUAV can resist. The lower boundary of the results is illustrated in Figure 13.

The maximum crosswind velocity that the QFHUAV can resist is 6 m/s. In this work, the step size of the Euler angles is set to 0.5° to solve equation (39), and this value provides a trade-off between the amount of calculations and the detail of the results. When the wind velocity is less than 2 m/s, the actual Euler angles of the QFHUAV are less than 0.5°. These Euler angles are too small to be recorded and graphed because of the large step size. This effect is the reason why the attitude of the QFHUAV does not change and the results line is vertical when the crosswind velocity is less than 2 m/s. These results show that the wind disturbance rejection capability of the QFHUAV in the quadrotor mode is poor in this situation.

The factors affecting the wind disturbance rejection capability and improvement approaches

From the above results and analysis, the wind disturbance rejection capability of the QFHUAV in the quadrotor mode is strong in the headwind situation and poor in the crosswind situation, and these findings agree well with the actual circumstances. Therefore, this section focuses on the factors affecting the wind disturbance rejection capability of the QFHUAV in the crosswind situation and corresponding improvement approaches.

The parameters in equations (30), (31) and (36) to (39) reveal that the factors affecting the wind disturbance rejection capability of the QFHUAV include the configuration parameters \( (d_1, d_2, Z_g, \text{and } \delta) \), the aerodynamic parameters \( (L_w, D_w, Y_w, M_x, M_y, \text{and } M_z) \), and the maximum thrust and torque of each quadrotor motor-rotor system \( (T_{\text{max}} \text{ and } Q_{\text{max}}) \). According to equation (20), \( Q_{\text{max}} \) can be expressed as a function of \( T_{\text{max}} \). The extent of the effects of these parameters on the wind disturbance rejection capability of the QFHUAV are analyzed using the design of experiment (DOE) method. Optimal Latin hypercube design (LHD)\(^{31}\) is used to generate the sample data. The number of levels of the factors is set to 2000. The upper and lower boundaries of the configuration parameter values are ±20% of the current values. The range of the aerodynamic parameter values is consistent with the range of the CFD results. The maximum thrust ranges from 100 N to 200 N. A Pareto diagram about the effect of each parameter on the wind disturbance rejection capability of the QFHUAV is shown in Figure 14.

The Pareto diagram shows that \( \delta, T_{\text{max}}, M_z, d_1, \text{and } d_2 \) are the parameters that have the greatest effects on
the wind disturbance rejection capability of the QFHUAV, and the effects of these parameters account for over 93% of the total. $M_z$ has a negative effect on the wind disturbance rejection capability of the QFHUAV, and this result means that the yawing moment from the wind disturbance is the main factor threatening the safe flight of the QFHUAV in the quadrotor mode. According to equation (7), the yawing control moment produced by the quadrotor propulsion system consists of the total yawing torque of the rotors $\sum Q_{zk}$ and the total yawing moment produced by the components of the quadrotor propulsion system thrusts ($T_{zk}$ and $T_{yk}$). $T_{zk}$ and $T_{yk}$ increase with increasing $\delta$, and their maximum values increase with increasing $T_{\text{max}}$. $d_1$ and $d_2$ are the moment arms of $T_{zk}$ and $T_{yk}$, respectively. An increase in these parameters ($\delta$, $T_{\text{max}}$, $d_1$, and $d_2$) can increase the maximum yawing control moment, which accounts for the positive effects of these parameters on the wind disturbance rejection capability of the QFHUAV.

The effect of $\delta$ on the wind disturbance rejection capability. Assuming that the rotor disk angle $\delta$ is a variable, the aerodynamic coefficients approximated using the EBF-NN model and the quadrotor propulsion system parameters in Figure 7 can be substituted into equation (39) to obtain the relationship between the maximum wind velocity $v_{\text{wmax}}$ that the QFHUAV can resist and the rotor disk angle $\delta$, and this relationship is shown in Figure 15.

As shown in Figure 15, the maximum wind velocity $v_{\text{wmax}}$ that the QFHUAV can resist is 6 m/s when $\delta$ is 0°, which coincides with the results shown in Figure 13. The maximum wind velocity $v_{\text{wmax}}$ increases with increasing $\delta$, and the rate of increase decreases when $\delta$ is greater than 0°. From the above analysis, the yawing moment from the wind disturbance is the main factor threatening the safe flight of the QFHUAV in the quadrotor mode. Because of the two sets of counter-rotating pairs of rotors, the total yawing torque of the rotors ($\sum Q_{zk}$) is usually too small to balance the disturbance moment. This effect accounts for the poor wind disturbance rejection capability of the QFHUAV when $\delta$ is equal to 0°. According to equation (5), an increase in $\delta$ can increase $T_{zk}$ and $T_{yk}$, which can increase the yawing control moment to improve the wind disturbance rejection capability of the QFHUAV. The moment arms of $T_{zk}$ and $T_{yk}$ reach their maximum values when $T_{\text{max}}$ is perpendicular to the diagonal of the quadrotor motor position, and this situation can provide the maximum control moment.

In a windless situation, the required thrust of each quadrotor motor-rotor system with a rotor disk angle equal to $\delta$ is given as

$$T_r = \frac{T_{\delta=0}}{\cos \delta}$$

where $T_r$ is the required thrust, and $T_{\delta=0}$ is the thrust of each quadrotor motor-rotor system with $\delta = 0^\circ$ in a windless situation. The required thrust $T_r$ is 1.035 times as much as $T_{\delta=0}$ when $\delta$ is equal to 15°, and this result indicates that the increase in the thrust is less than 4%. In general, $\delta$ is less than 15°, and the VTOL time is short. Therefore, the rotor disk angle can improve the wind disturbance rejection capability of the QFHUAV in the quadrotor mode without significantly increasing the power consumption.

The effect of $T_{\text{max}}$ on the wind disturbance rejection capability. The maximum thrust of each quadrotor motor-rotor system ($T_{\text{max}}$) changes in the range of 100 N to 200 N. Under existing technologies, an increase in the maximum thrust of the propulsion system is
always accompanied by increases in the weights of the quadrotor propulsion system and the energy system. When the total weight of the quadrotor propulsion system and the energy system increases linearly, the linear relationship between the maximum thrust and the total weight can be substituted into equation (39) to obtain the effects of the changes in the maximum thrust \( T_{\text{max}} \) on the wind disturbance rejection capability of the QFHUAV for a given \( \delta \), and these effects are illustrated in Figure 16(a). Considering the improvement of technologies, assuming that the total weight of the quadrotor propulsion system and the energy system does not change with the changes in the maximum thrust of the quadrotor motor-rotor system, the effects of the changes in the maximum thrust \( T_{\text{max}} \) on the wind disturbance rejection capability of the QFHUAV are illustrated in Figure 16(b).

As shown in both figures, when the rotor disk angle \( \delta \) is small, an increase in the maximum thrust cannot significantly improve the wind disturbance rejection capability of the QFHUAV. However, an increase in the maximum thrust is effective for improving the wind disturbance rejection capability of the QFHUAV when the rotor disk angle \( \delta \) is large. An increase in the maximum thrust can improve the wind disturbance rejection capability of the QFHUAV effectively when the maximum thrust is small.

A comparison of the results in Figure 16(a) and (b) shows that the wind disturbance rejection capability of the QFHUAV is stronger when the weight increases than when the weight is constant, and this result indicates that an increase in the weight can improve the wind disturbance rejection capability of the QFHUAV. This finding is consistent with common sense. Because an increase in the weight has negative effects on the performance of the QFHUAV, such as on the endurance and flight speed, it is unreasonable to increase the weight from this point of view. Therefore, under existing technologies, the determination of the quadrotor propulsion system requires a trade-off between the wind disturbance rejection capability and other performance aspects such as endurance.

The effect of \( d_1 \) and \( d_2 \) on the wind disturbance rejection capability. When the QFHUAV can resist a crosswind with velocity \( v_w \), \( d_1 \) takes different values in the range of 0.5 m to 1 m, and \( \delta \) takes different values in the range of \( 0^\circ \) to \( 15^\circ \), the required minimum value of \( d_2 \) in the range of 0.5 m to 1 m can be obtained by solving equation (39). The results are shown in Figure 17 for crosswind velocities 6 m/s, 8 m/s, 11 m/s, and 12 m/s.

The results in Figure 17(a) show that \( d_2 \) can take any value between 0.5 m and 1 m for any values of \( d_1 \) and \( \delta \) when the crosswind velocity is less than 6 m/s. A comparison of the results in Figure 17 shows that the required lengths of \( d_1 \) and \( d_2 \) increase with increasing wind velocity for a given \( \delta \). For a constant wind velocity, the required lengths of \( d_1 \) and \( d_2 \) decrease with the increasing \( \delta \). It can be concluded that the increases in \( d_1 \) and \( d_2 \) can improve the wind disturbance rejection capability of the QFHUAV and that the effects of \( d_1 \), \( d_2 \), and \( \delta \) on the wind disturbance rejection capability of the QFHUAV are coupled.

The yawing moment from the wind disturbance is small when the wind velocity is less than 6 m/s. The required yawing control moment is small so that the minimum values of \( d_1 \), \( d_2 \), and \( \delta \) can meet the requirement. The required yawing control moment increases with increasing the wind velocity, resulting in a need to increase the lengths of the moment arms \( d_1 \) and \( d_2 \) and the thrust values \( T_{\text{xk}}, T_{\text{yk}} \). From the above analysis, \( T_{\text{xk}} \) and \( T_{\text{yk}} \) increase with increasing \( \delta \). The required yawing control moment is constant for a constant wind velocity. Thus, an increase in \( \delta \) reduces the required lengths of \( d_1 \) and \( d_2 \), and vice versa.
As shown in Figure 18, there are two main types of QFHUAV layouts at present. One layout can be called H-type, which features the quadrotor propulsion system supported by the wing structure. The other layout can be called X-type, which features the quadrotor propulsion system supported by the fuselage structure. For a QFHUAV with an H-type layout, in the quadrotor mode, the wing is subjected to the concentrated load at the quadrotor propulsion system supported rod installation position. An increase in the lengths of \( d_1 \) and \( d_2 \) results in the wing being subjected to a greater bending moment and twisting moment under the same load, this effect correspondingly increases the requirements of the strength and stiffness of the wing structure, which significantly increases the structure weight of the QFHUAV. Thus, the lengths of \( d_1 \) and \( d_2 \) should be as small as possible to meet the requirements of the structure layout and the wind disturbance rejection capability. The corresponding \( d \) should be larger to reduce the required lengths of \( d_1 \) and \( d_2 \). In addition, the support structure of the quadrotor system should use the QFHUAV layout that more easily adjusts the lengths of \( d_1 \) and \( d_2 \) without significantly increasing the structural weight. From this perspective, a QFHUAV with an X-type layout is more reasonable and efficient.

The effect of \( M_z \) on the wind disturbance rejection capability. The body of the QFHUAV is divided into six parts: the wing, fuselage, horizontal tail, vertical tail, quadrotor motor rotor system, and quadrotor propulsion system support rods. The percentage of the yawing moment generated by each part in the total aerodynamic

![Figure 17. The required values of \( d_1, d_2 \) and \( \delta \) at a given wind velocity. (a) \( v_w = 6 \text{ m/s} \); (b) \( v_w = 8 \text{ m/s} \); (c) \( v_w = 11 \text{ m/s} \); (d) \( v_w = 12 \text{ m/s} \).](image)

![Figure 18. Main types of the QFHUAV layout.](image)
The yawing moment of the QFHUAV is simulated using the CFD method. The results are shown in Figure 19 when the Euler angles are \([0^\circ, 0^\circ, 0^\circ]^T\).

The results show that the yawing moments generated by the fuselage and the quadrotor propulsion system support rods are close and that their directions are opposite. The yawing moment generated by the vertical tail is much larger than that generated by the other parts. Therefore, this section mainly focuses on the effect of the vertical tail on the wind disturbance rejection capability of the QFHUAV in the quadrotor mode.

The maximum wind velocity is set to 15 m/s. The vertical tail is removed to evaluate the effect of the vertical tail on the wind disturbance rejection capability of the QFHUAV in the following two cases: (a) \(d_1 = d_2 = 0.7\,\text{m},\ \delta = 0^\circ\); (b) \(d_1, d_2 \in [0.5\,\text{m}, 1\,\text{m}],\ \delta \in [0^\circ, 15^\circ]\). By solving equation (39), the wind disturbance rejection capability of the QFHUAV without the vertical tail and that of the QFHUAV with the vertical tail in both cases are shown in Figure 20. The comparison results show that the wind disturbance rejection capability of the QFHUAV without the vertical tail is stronger than that of the QFHUAV with the vertical tail. This finding indicates that the vertical tail is a significant factor leading to the poor wind disturbance rejection capability of the QFHUAV. The optimum design of the vertical tail is a necessary approach to improve the wind disturbance rejection capability of the QFHUAV. In addition, from the perspective of the wind disturbance rejection capability, a tailless layout is a better choice for the QFHUAV.

## Flight test

Two test schemes are designed to verify the correctness of the proposed method. The Fully Autonomous Control mode of the Shining autopilot from XY-UAV company is used in the test. (a) As shown in Figure 21(a), a test frame that consists of a support...
frame, pulley and rope is designed and constructed. In the quadrotor mode, the QFHUAV is tied hanging from the support frame by the rope, and the tightness of the rope is controlled through the pulley. The rope is loose when the QFHUAV is controllable and tight when the QFHUAV is out of control. Wind patterns in urban environments are fast time-varying and uncontrollable. In this work, the wind velocity used to determine the wind disturbance rejection capability is the average within 3 s. In addition, the maximum average wind velocity is 10 m/s due to the limitations of the wind field environment of the test site. (b) As shown in Figure 21(b), in a windless situation, when the QFHUAV flies forward and sideways in the quadrotor mode at a constant speed, the control mode and the forces and moments acting on the QFHUAV are close to those of the QFHUAV hovering in the headwind and crosswind situations, respectively. The maximum flight speed of the QFHUAV in the quadrotor mode can be used to measure the wind disturbance rejection capability.

Because it is hard to predict the wind patterns at the test site and build QFHUAVs with different layouts, the flight test is time consuming, laborious and costly. Thus, only the wind disturbance rejection capabilities of the QFHUAV layouts with configuration parameters shown in Table 5 are tested. The scheme that changes the configuration parameters is shown in Figure 22.

The results obtained from the test frame and the flight test and the theoretical results obtained by the proposed method are shown in Figure 23. The test results are in good agreement with the results obtained by the proposed method. Although the results are slightly different, taking the errors of aerodynamic and quadrotor propulsion system models and the simplification of the proposed method to the problem into account, the error between the test results and the theoretical results is reasonable. In addition, in scheme (a), even if the average wind velocity is small, the instantaneous wind speed may be too large to resist. In scheme (b), to prevent the QFHUAV from crashing, the flight test in the quadrotor mode cannot reach the safety boundary. Both of the above facts are the reasons why the determined wind velocity that the QFHUAV can resist in the flight test may be slightly smaller than that obtained by the proposed method. Nevertheless, the trend of the results of the proposed method is similar to that of the test results.

Table 5. The parameters of the QFHUAV layouts being tested.

| No. | δ, degree | d1, m | d2, m | With vertical tail |
|-----|-----------|-------|-------|-------------------|
| 1   | 0         | 0.7   | 0.7   | Yes               |
| 2   | 0         | 0.7   | 0.7   | No                |
| 3   | 5         | 0.7   | 0.7   | Yes               |
| 4   | 5         | 0.7   | 0.7   | No                |
| 5   | 10        | 0.7   | 0.7   | Yes               |
| 6   | 10        | 0.7   | 0.7   | No                |

Figure 22. A CATIA model of the scheme that changes the configuration parameters.

Figure 23. The flight test results. (a) With vertical tail; (b) Without vertical tail.
Conclusion

In this paper, a method for analyzing and evaluating the wind disturbance rejection capability of a QFHUAV in the quadrotor mode is presented based on static equilibrium analysis of the quadrotor mode of the QFHUAV with a wind disturbance. Through the proposed method, the wind disturbance rejection capability of an example QFHUAV is analyzed efficiently and accurately. The factors affecting the wind disturbance rejection capability of the QFHUAV are explored, and include the configuration parameters, the aerodynamic parameters and the maximum thrust and torque of each quadrotor motor-rotor system. Corresponding improvement approaches are analyzed and tested. Based on the theoretical and test results, the following conclusions are drawn:

a. In the quadrotor mode, the wind disturbance rejection capability of the QFHUAV is strong in the headwind situation, and a low-speed headwind can be used to reduce the power consumption of the quadrotor propulsion system. The wind disturbance rejection capability of the QFHUAV is poor in the crosswind situation. The yawing moment from the wind disturbance is the main factor threatening the safe flight of the QFHUAV in the quadrotor mode.

b. An increase in the rotor disk angle can improve the wind disturbance rejection capability of the QFHUAV without significantly increasing the power consumption. Increasing the maximum thrust of the quadrotor propulsion system and the weight of the vehicle and extending the moment arms of the components of the quadrotor propulsion system thrust are also effective approaches to improve the wind disturbance rejection capability of the QFHUAV in the quadrotor mode. The situation when the thrust of the rotor is perpendicular to the diagonal of the quadrotor motor position can provide the maximum yawing control moment. Under existing technologies, the determination of the quadrotor propulsion system requires a trade-off between the wind disturbance rejection capability and other performance aspects such as endurance.

c. The yawing moment generated by the vertical tail is much larger than that generated by the other parts in the crosswind situation, and this result means that vertical tail is the main part generating the yawing moment. The optimum design of the vertical tail is a necessary approach to improve the wind disturbance rejection capability of the QFHUAV in the quadrotor mode.

d. From the perspective of wind disturbance rejection capability, tailless and X-type layouts are better choices for QFHUAVs.

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