Vectored Thrust eVTOL Takeoff/Landing Control Strategies under Crosswind Conditions

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Abstract

Vectored thrust eVTOL are susceptible to attitude instability and even trajectory deviation during takeoff/landing phases under crosswind conditions. This paper focuses on the crosswind resistance capability of vectored thrust eVTOL. Firstly, a coupled simulation model of flight dynamics and control law for vectored thrust eVTOL and a wind field model are established. Then, based on ADS-33, an evaluation method for the crosswind resistance capability of eVTOL was established. The parameters such as rotor speed, climb rate and approach strategies were analyzed. Finally, the simulation results show that increasing the rotor speed during takeoff and landing, lower climb rate, wing-down approach strategy can enhance the crosswind resistance capability.

1. NOTATION

Symbols

a	Aircraft acceleration, m/s^2
q	Pitch rate, rad/s
r	Yaw rate, rad/s
V_0	Velocity of the blade element, m/s
V_a	Velocity in the inertial frame, m/s
V_i	Induced velocity, m/s
V_{wind}	Wind velocity, m/s
V	Aircraft velocity, m/s
θ	Pitch, rad
ψ	Yaw
δ_{Lon}	Control of longitudinal channel
δ_{Yaw}	Control of yaw channel
X	Longitudinal axis
Y	Lateral axis
set	Set value
fbk	Feedback value

Acronyms:

ERF	European Rotorcraft Forum
VFS	Vertical Flight Society
eVTOL	electric Vertical Take-Off and Landing

2. INTRODUCTION

Urban Air Mobility (UAM) holds immense potential in mitigating traffic congestion and environmental pollution prevalent in densely populated urban areas. The pivotal enabler for the realization of UAM lies in electric Vertical Take-Off and Landing (eVTOL) aircraft(Ref .1)

Vectored thrust, literally meaning that eVTOLs can change the direction of the thrust force. Usually, vectored thrust eVTOL has a higher lift-to-drag ratio during cruise, thus generally having a greater cruise speed and range.

Vectored thrust will lead to the nonlinearity and strong coupling of flight dynamics, particularly in the transition region of the aircraft. The transition region is the most distinctive feature of vectored thrust eVTOL. Most of the related research focuses on the design of transition strategy(Ref .2) , or the optimization of transition trajectory (Ref .3). However, apart from the difficulty about control in the transition region, there are also potential risks during the take-off and landing phases. This is because most vectored thrust eVTOL are designed for optimized level-flight performance. And this practice inevitability results in relatively poor flight performances, such as crosswind resistance performance, when the eVTOL in or near the hover mode(Ref .4).

Till now, lots of control algorithms have been studied and applied in vectored thrust eVTOL. Papachristos(Ref .5) designed a PID controller for tilt rotor, WANG(Ref .6) design a controller based on improved

ADRC for Tilt Quad Rotor, Stefan Raab(Ref .7) proposes a unified controller based on an Incremental Nonlinear Dynamic Inversion (INDI) for vectored thrust eVTOL. These control laws are designed with the assumption that wind is an external disturbance. However, there is a lack of analysis or simulation regarding the influence of wind on the attitude and trajectory of eVTOL.

For other configurations of eVTOL, there are some studies on crosswind resistance strategies and analysis of the influence of wind fields. Li(Ref .8) showed that the lift-and-roll type EVTOL has weak lateral crosswind resistance capability during the deceleration stage and a control strategy for crosswind resistance has been proposed. Lombaerts(Ref .9) applied INDI for integrated full envelope flight control of a lift plus cruise eVTOL vehicle. A wind field model for San Francisco was established and the landing process of eVTOL was simulated. Without wind, the deviation of the landing position from the target point was 1.2m, but with the wind field considered, this distance changed to 3.8m.

During takeoff and landing, the airspeed is relatively low and the control surfaces cannot provide sufficient control power. Vector thrust eVTOL mainly relies on the rotor system for control, similar to multi-rotor aircraft. The yaw control power of multi-rotor aircraft is relatively low. Vector thrust eVTOL usually has a greater inertia in the yaw direction than multi-rotor aircraft, thus making the heading control more difficult and making it harder to maintain a fixed flight path. For safety considerations, eVTOL should be managed in accordance with civil aviation during operation. Therefore, during the approach process, eVTOL should remain on a fixed flight path. Thus, how to improve the crosswind resistance capability of vector thrust eVTOL so that it can remain within the required safety separation during the approach process lack of relevant research.

At present, there is no generally accepted evaluation method for the crosswind resistance performance of eVTOL aircraft. Favaro(Ref .11) studied the method of obtaining evtol handling quality data through simulation, but the wind field was not taken into consideration. David(Ref .12) conducted a preliminary study on the handling quality and certification of evtol, but the research on aspects such as airworthiness certification is still ongoing.

This paper builds further on the work of Li(Ref .10), who proposed a modeling method based on multi-body dynamics for real-time simulation of vectored thrust eVTOL. Based on this, this paper adds the wind field model, thus forming a verification platform for the crosswind resistance strategy. Due to insufficient research on crosswind rejection strategies and crosswind-resistant design methodologies for vectored thrust eVTOL aircraft, coupled with ongoing development of handling qualities evaluation frameworks, this study employs flight simulation techniques to conduct a series of parametric influence analyses based on ADS-33E(Ref .13). These analyses provide critical insights for the conceptual design and flight controller synthesis of vectored thrust eVTOL systems.

The structure of this article is shown as follows. Section 3 introduces the flight dynamic model and wind field model, as well as the vectored thrust eVTOL model used for simulation verification; Section 4 conducts parameter influence analysis; Section 5 presents the simulation results and analysis.

3. EVTOL MODELING AND VALIDATION

3.1. Evtol Modelling Method

In this paper, the flight dynamics model of eVTOL is established based on multi-body dynamics method.

Each blade is independently modeled as rigid body and connected to the rotor shaft through hinges, as illustrated in Figure 1. For common eVTOLs, since the blade size is relatively small, the influence of blade elastic deformation can be disregarded.

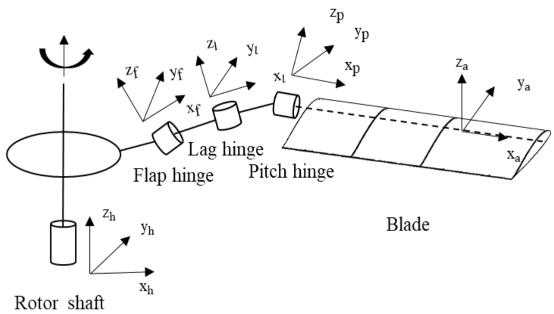

Figure 1: Schematic diagram of Single-Blade Structures in Rotor Systems

The velocity of the blade element V_0 is calculated in Eq. (1).

(1) $$V_0 = V_a + V_i + V_{wind}$$

Here, V_a represents the velocity of the blade element in the inertial frame of reference. V_i represents the induced speed of the rotor. V_{wind} represents the wind speed. This paper does not take into account the aerodynamic interference of components such as rotors and wings on the rotors. Based on the blade element theory, a two-dimensional airfoil aerodynamic database is utilized to compute the aerodynamic forces acting on each blade element.

Dynamic inflow(Ref .14) is used to calculate the induced velocity V_i distribution of rotor disk. The specific formula can be found in Eq. (2).

$$M\begin{Bmatrix}\dot{v}_0\\ \dot{v}_s\\ \dot{v}_c\end{Bmatrix}+L^{-1}\begin{Bmatrix}v_0\\ v_s\\ v_c\end{Bmatrix}=\begin{Bmatrix}C_T\\ C_L\\ C_M\end{Bmatrix} \tag{2}$$

where v_0, v_s, and v_c, are the uniform, lateral, and longitudinal variations in rotor inflow, respectively. M is the matrix of the apparent mass terms, L is the nonlinear version of the inflow gains matrix, C_T, C_L and C_M are the instantaneous rotor thrust, and roll and pitching moment coefficients, respectively.

The wings are modelled as rigid bodies. The aerodynamic forces acting on the wings are computed using Vortex Lattice Method(VLM, Ref .15).

The fuselage is modeled as a six-degree-of-freedom rigid body. The aerodynamic forces and moments acting on the fuselage are determined by utilizing experimental data obtained from wind tunnel tests.

The tilting mechanism of the eVTOL aircraft is modelled as a combination of a revolute joint and a prismatic joint.

Since the main focus of this study is on the performance of eVTOL at low speeds, the aerodynamic interference model based on the slip stream theory is not applicable, and the aerodynamic interference model based on VPM is computationally too demanding. Therefore, aerodynamic interference is not considered in this paper.

This study employs the Lagrange equations of the second kind to model multi-body systems. Unlike the first-class Lagrange equations, the generalized coordinates and velocities in the Lagrange equations of the second kind directly correspond to the system's motion state, eliminating the necessity to address redundant constraint equations. Consequently, the physical interpretation of the state variables in the model becomes more intuitive, thereby enhancing comprehension and analysis. Moreover, the reduced variable count in the equations, coupled with pure differential equations, enables more effective utilization of numerical integration and optimization algorithms.

This paper establishes a wind field model in order to apply it to the subsequent studies on crosswind-related issues. The wind field model includes the average wind model, the atmospheric turbulence model and the gust model. Among them, the average wind model needs to take into account the variation law of the wind speed profile. This paper adopts the exponential law to fit the wind speed profile. This paper adopts the Von Karman atmospheric turbulence model. Compared with the turbulence model, the discrete gust can represent the large disturbance wind types that do not satisfy the Gaussian assumption. For example, the discrete gust can describe the wind shear caused by the inversion phenomenon, the disturbance brought by the tip vortex, or the sudden change of the flow field environment, etc. In practical engineering applications, the discrete gust model can be used together with the turbulent model to better reflect the pulsating characteristics of the wind. This paper uses the half-wavelength 1-cosine type gust model, an example of the combination of gust and turbulence is shown in Figure 2

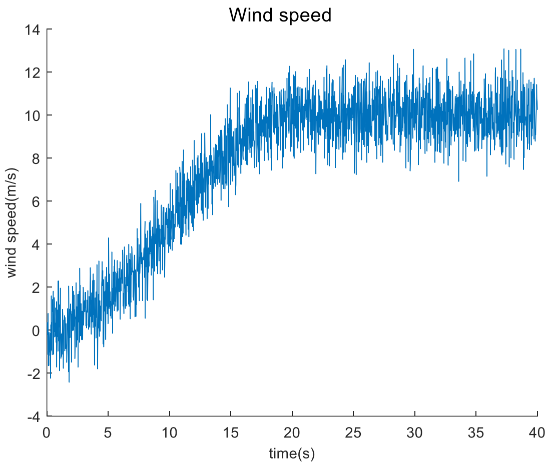

Figure 2: Schematic diagram of the combination of gust and turbulence

3.2. Modelling Method Validation

The modeling methods for each part have been verified through detailed examples in Ref .10. However, there are no verification examples for the entire eVTOL.

Due to the lack of flight data of evtol helicopter to validate the modeling method, a typical helicopter UH-60A(Ref .1615). with abundant experimental data is used to validate the modeling method. The main modeling parameters are shown in Table 1. The main rotor was modeled as flapping hinge and rigid blades, the tail rotor was modeled as rigid hub and rigid blades. The aerodynamic forces of the rotor blades are calculated according to the model mentioned above. The fuselage and vertical and horizontal tails were modeled as rigid body while the aerodynamic force is modeled according to Ref .16.

Table 1: UH-60A Aircraft Characteristics.

	Characteristic	Value
Main Rotor	Radius	8.178m
	Chord	0.526m
	RPM	27rad/s
Tail Rotor	Radius	1.676m
	Chord	0.247m
	RPM	124.6rad/s

Firstly, the validity of the modeling method is verified by checking the trim values. The trim results of the uh-60a model are shown in Figure 3 and Figure 4. The attitude and control of the aircraft are in good agreement with the experimental values. The trim state and experimental values are from ref 17.

Then, examine the model's response in the maneuvering state. According to the operation method in ref 18., when in the hovering state, push the control stick forward. The rate response of the aircraft's pitch rate is shown in Figure 5. It can be seen that in the maneuvering state, the response of the aircraft is basically in line with the experimental values.

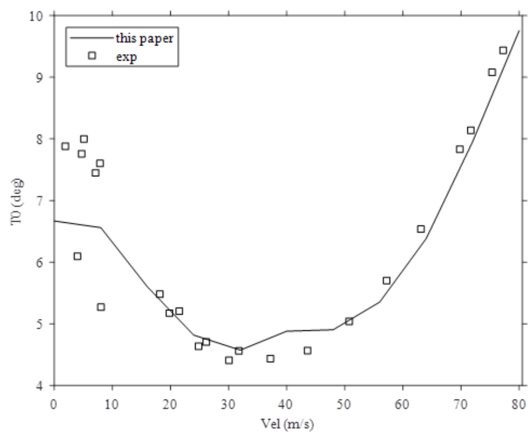

Figure 3: The curve of T0 varying with flight speed

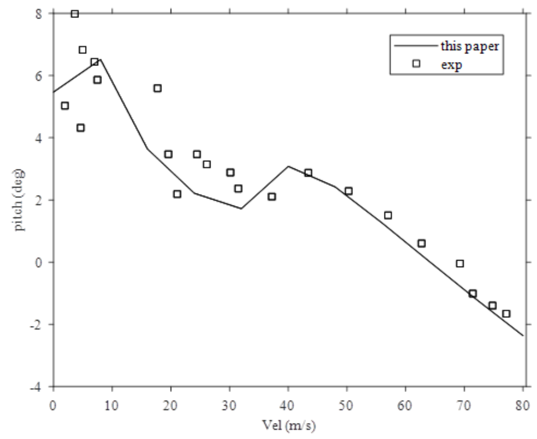

Figure 4: The curve of pitch varying with flight speed

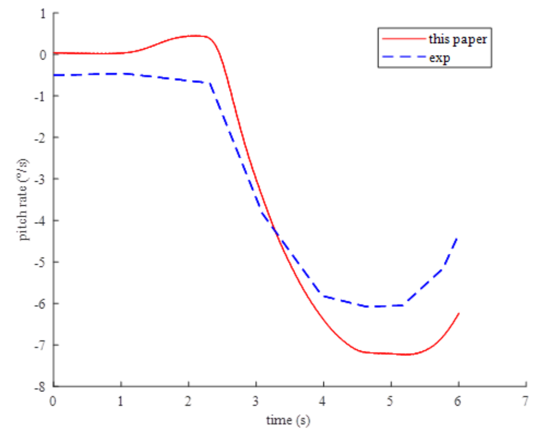

Figure 5: The response of push the control stick in the hover mode

3.3. eVTOL Model

This paper establishes an eVTOL with 6 independently tiltable rotors as the research object. The configuration of this eVTOL is shown in Figure 6.

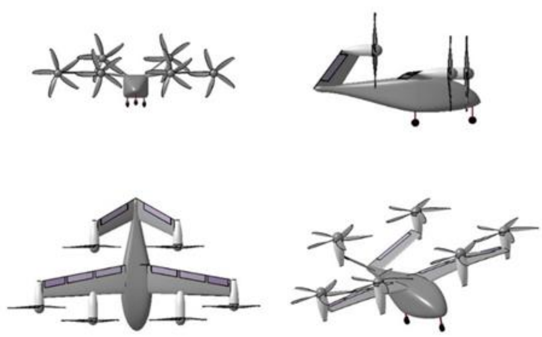

Figure 6: Schematic diagram of eVTOL

Each rotor is made up of five-blade propeller with a rigid hub, which allows pitch and rotation speed variation during flight. The shape of the propeller is based on the ATB propeller, with the same twist and airfoil distribution and an increased solidity.

Taking into consideration that the propeller contains a rigid hub and an electrical propeller pitch control mechanism, no flapping, lagging and pitching hinges are set during modelling. As for aerodynamic modelling, each propeller is divided into 18 units.

A low aspect ratio straight wing is adopted, with airfoil of NACA64A223, maximum lift coefficient of 1.75, stall AOA of about 16°, and ailerons. Each side of the wing is divided into 20 vortex lattices, with 2 rows along chord direction, and the second row includes the vortex lattices where the ailerons are located.

A V-shaped tail wing is adopted, with a symmetrical airfoil of NACA64A15, maximum lift coefficient of 1.4, and stall AOA of about 16°. Each side of the tail wing is divided into 20 vortex lattices, which are divided into 2 rows along the chord direction, and the 2nd row includes the vortex lattices where the elevator is located.

The ROBIN fuselage is adopted.The aerodynamic interference of all rotors to the wing and tail wing is considered, as well as the aerodynamic interference of the two inner-front rotors to the two rear rotors.The separate dynamics models of each eVTOL component are stitched together to obtain the flight dynamic model of the whole aircraft.

The mathematical model of the whole aircraft can be written in the form of ODE. The equation has a total of 6 variables, namely the 6 degrees of freedom for the rigid body movements of the aircraft body. The newmark-beta method is used for the solution and the time step is fixed at 10ms.

The design parameters of the model are shown in Table 2.

Table 2: eVTOL Model Aircraft Characteristics.

	Characteristic	Value
Aircraft	Take-off Weight (TOW)	2000 kg
	Cruise Speed	80 m/s
	Minimum Forward-Flight Speed (Fixed Wing)	50m/s
	Radius	1.5 m
Propellers	Number of Blades	5
	Solidity	0.2417
	Blade Tip Speed	120-180 m/s
Main Wing	Airfoil	NACA64A223
	Wingspan	8 m
	Root Chord	1.36 m
	Taper Ratio	0.57
	Sweep Angle	-4 deg
Tail Wing	Airfoil	NACA64A15
	Average Chord	0.9 m
	Taper Ratio	0.82
	Sweep Angle	-21.8 deg
	Dihedral Angle	38 deg

This paper mainly studies the flight dynamics characteristics of evtol at low-speed stages. Therefore, only the control law of the multi-rotor mode is considered.

In the longitudinal axis and roll axis, there are velocity hold systems. In the yaw axis and height axis, there are attitude/height command systems.

The velocity hold system used in this paper is shown in Figure 7. It consists of 2 circuits.

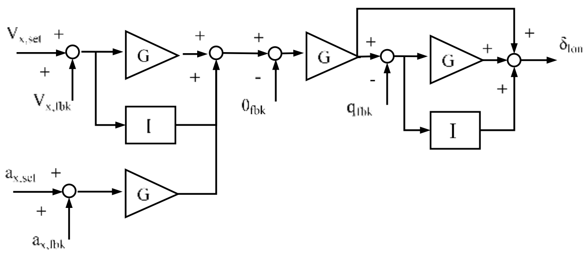

Figure 7: X-axis velocity hold system

The velocity hold system comprises two loops. The outer loop is the longitudinal velocity (X-direction) loop. This loop employs a PID controller to generate the target pitch angle. The target pitch angle is then subtracted from the measured (feedback) pitch angle, and this error signal is amplified by a proportional gain. The result of this proportional action is the target angular rate command for the inner loop. The inner loop processes this target angular rate through a PI controller augmented with feedforward. The output of this inner loop controller is the longitudinal channel command, denoted as $\delta_{\rm lon}$. The value with the subscript "set" is the set value, and the value with the subscript "fbk" is the feedback value. Y-axis velocity hold system has the same structure.

The heading hold system(Figure 8) employs a single control loop. The target yaw angle is compared to the measured feedback yaw angle, and the resulting error signal is scaled by a proportional gain. The output of this proportional action serves as the target yaw rate command for the loop. This target yaw rate is then processed by a PI controller. The output of the PI controller is the yaw control δ_{yaw}

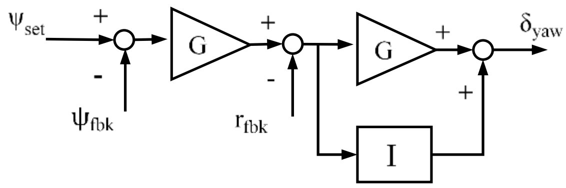

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Figure 8: Heading hold system

4. PARAMETRIC STUDY

4.1. General

The pitch and roll channels of vectored thrust eVTOL have relatively high control power while the yaw channel has relatively low control power. Therefore, vectored thrust eVTOL is more sensitive to the heading disturbance caused by lateral gust. Since eVTOL is a new type of aircraft that emerged in recent years, there are currently no relevant quality specification requirements for it. ADS-33 is accepted internationally as a valuable design guide for rotorcraft handling qualities.

The elements related to gust response and heading response in ADS-33 include yaw response to yaw controller, yaw rate response to lateral gusts, and position hold etc.

Due to over-actuated control systems and complex control laws, traditional mission task elements in ADS-33 may not be appropriate or entirely sufficient.

In the subsequent research, this paper expands upon subject ‘yaw rate response to lateral gusts’ and examines yaw, roll, lateral position to lateral gusts.

The specific element is consider the eVTOL flying at a steady forward speed of 20 m/s. The tilt angles of all six rotors are stabilized at 3°, and the rotational speeds remain consistent and unchanged. Under steady state conditions, a lateral gust is applied. The average wind speed of the gusts is 5m/s(light winds), 10m/s(moderate winds) and 15m/s (moderate winds).

Obviously, the parameters of the control law have a significant impact on the results of crosswind disturbances. In this study, when conducting comparisons of different parameters, the controller parameters will be adjusted to achieve the most desirable results.

4.2. The influence of rotor speed and gust speed

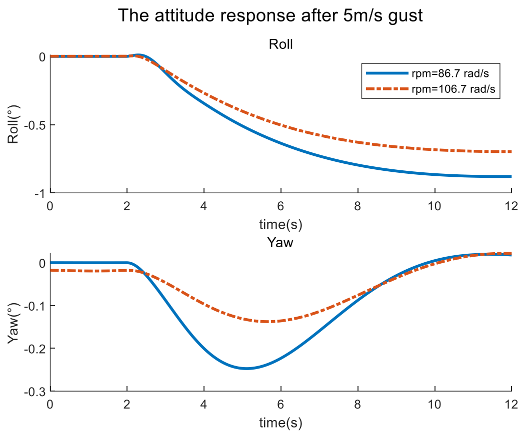
Usually, the rotor speed of eVTOLs is low in order to reduce noise. However, an low rotor speed may affect the eVTOL’s ability to resist wind turbulence.

The simulation results are shown in Figure 9 and Figure 10. It can be seen that during forward flight, using a higher rotor speed (lower collective pitch) can enhance the response speed of the roll angle after being disturbed by gusts, enabling a faster convergence to the steady state and maintaining smaller attitude angles in a stable crosswind. Similarly, the lateral position shift is smaller at higher rotor speed but there is more variation in altitude. Moreover, as can be observed from Figure 9.(c), a higher rotor speed can maintain stability even under more intense gust disturbances. This might be because at low rotational speeds, the collective pitch of the rotor blades is greater, and the effective angle of attack of some sections is closer to the stall angle of attack. The rotor pull force is not sensitive to the change in collective pitch, thus reducing the control efficiency.

There is a notable phenomenon, the conclusion about yaw response to lateral gusts depending on the different gust speeds. This might be related to the heading hold system of the eVTOL. However, since the value of yaw is relatively small and can converge, what we are more concerned about is the lateral position, which results are consistent under different gust speeds.

Finally, for a gust speed of 15 m/s (which is considered a relatively strong moderate wind in ADS-33), with the low rotor speed of the eVTOL, it cannot maintain stability after flying for a period of time; instead, it enters the Dutch roll mode.

In the subsequent research of this paper, the rotor speed is set as 86.7 rad/s.



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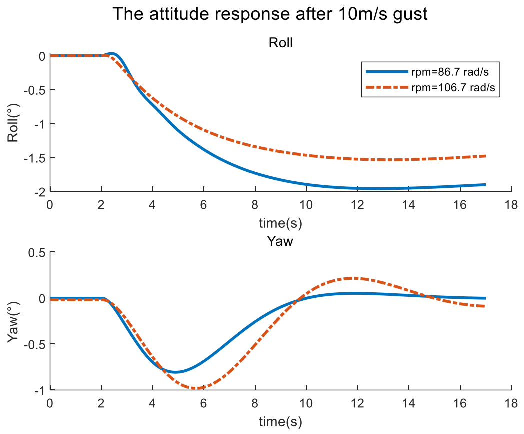

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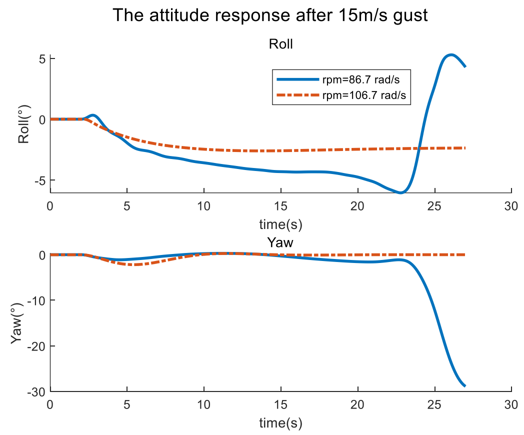
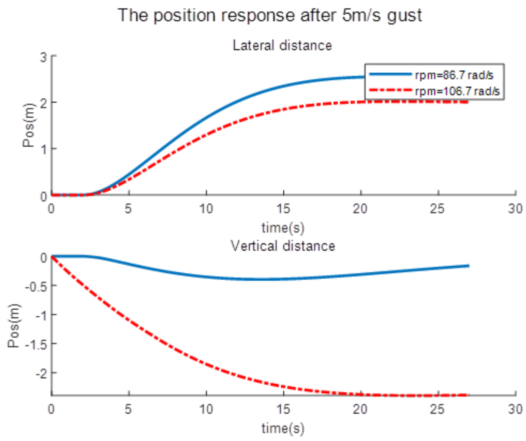


(c)

Figure 9: The attitude response after lateral gust



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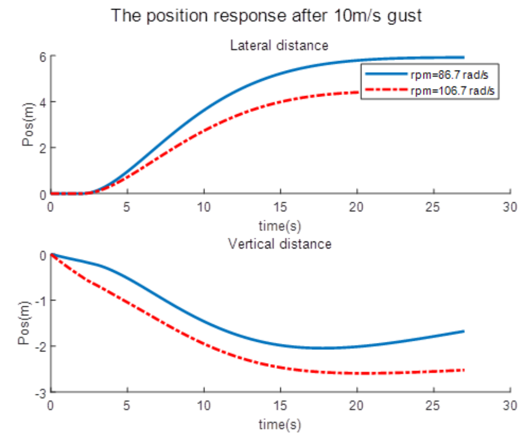

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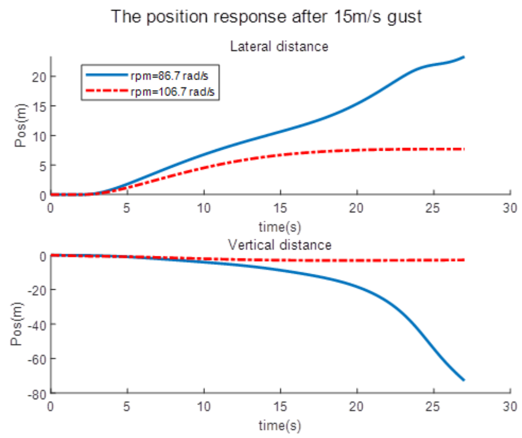


(c)

Figure 10: The position response after lateral gust

4.3. The influence of climb rate

In Section 4.2 of the study, eVTOl was in a level flight state. Now, we are considering a climb rate of ±2 m/s. The simulation results are shown in Figure 11 and Figure 12.

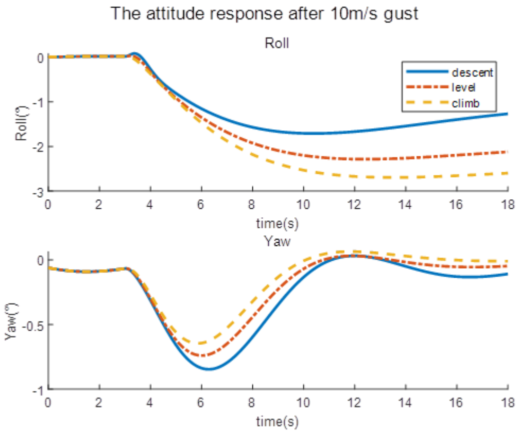


Figure 11: The attitude response after lateral gust

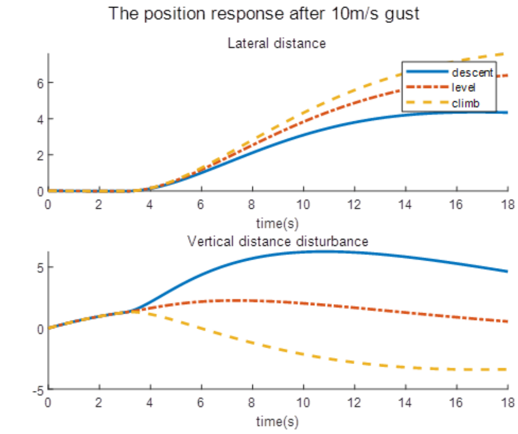


Figure 12: The position response after lateral gust

It can be seen that the climb rate has opposite effects on the pitch angle response and the roll angle response. Similarly, its influence on lateral distance and vertical distance is also opposite.

Overall, the influence of the climb rate is similar to that of the rotor speed. This can also be explained from the perspective of the effective attack angle of the propeller. During descent, the blade angle of the propeller is smaller compared to that during climb, so it is less sensitive to gust.

4.4. The influence of approach strategy

For fixed-wing aircraft, a successful approach in crosswind conditions means that the aircraft established on the glide path and the aircraft ground speed vector lined up with the centerline of the runway.

Van Es (Ref .19) showed there are two procedures are commonly employed to counteract crosswind conditions during an approach . The first method involves using the "crabbed" technique, where the aircraft is oriented slightly into the wind. The second technique, known as the "wing-down" method, involves executing a controlled sideslip to offset the drift induced by the crosswind. The methods are shown in the Figure 13.

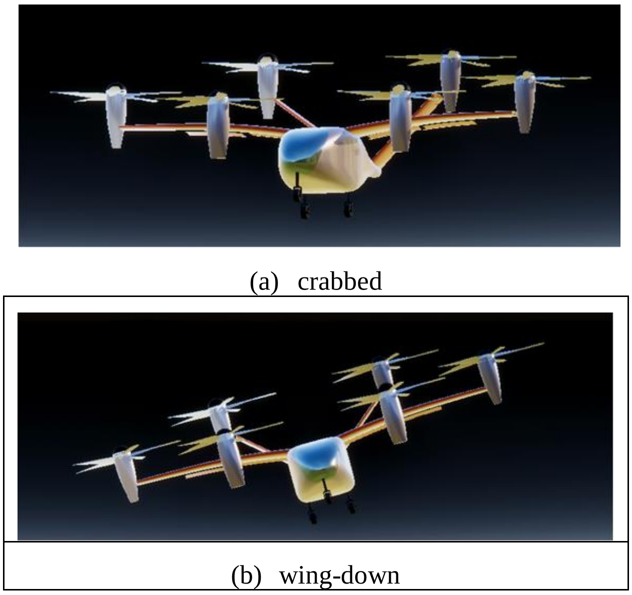


Figure 13: Schematic of different approach strategies

The controller mentioned in the previous text involves an approach in the "wing-down" mode. Modifying the Y-axis velocity and heading hold system will result in the Y-axis velocity hold system for the crabbed mode. Please refer to the Figure 14 for details.

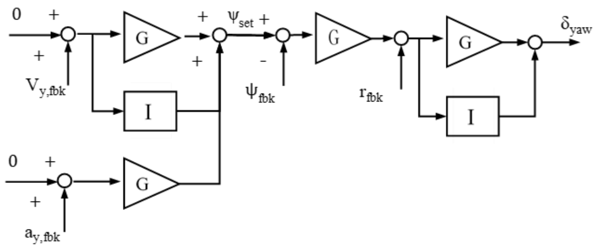


Figure 14: Y-axis velocity hold system (crabbed)

The simulation results are shown in Figure 15 and Figure 16. It can be seen that the performance of the crabbed mode is much worse than that of the wing-down mode. The eVTOL took approximately 30 seconds to rotate by about 40 degrees in the heading angle, which enabled the lateral distance to stabilize. This is unacceptable in actual flight conditions. This is partly because eVTOL have less control power in yaw axis, and partly because the flight speed of eVTOL is much lower than that of fixed-wing aircraft during approach, so the heading angle needs to rotate much more than the usual fixed-wing rotation angle.

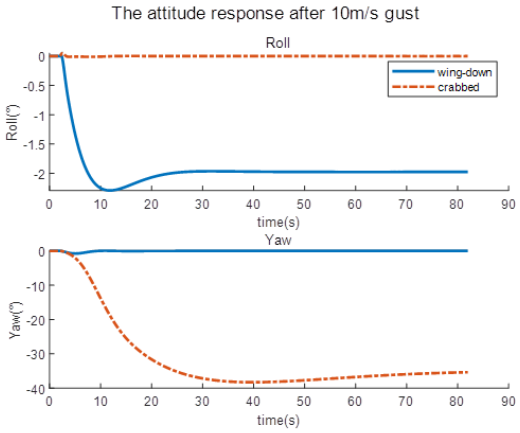


Figure 15: The attitude response after lateral gust

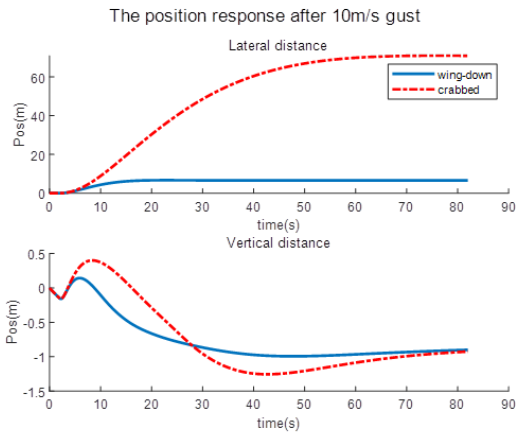
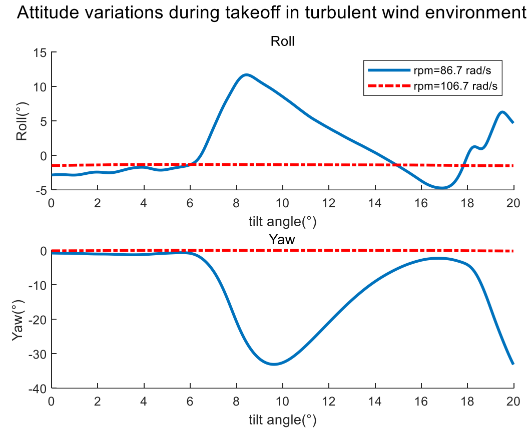


Figure 16: The position response after lateral gust

4.5. Takeoff simulation

Based on the previous research, the process of take-off was simulated at different rotor rotational speeds. The wind field is characterized by a lateral turbulence wind with an average speed of 10 m/s. The results are shown in Figure 17. During takeoff, using a lower rotor speed is insufficient to resist the disturbance wind. In this case, the attitude of evtol changes drastically, entering the Dutch roll mode, and cannot be maintained at a constant altitude. This shows that the takeoff process is prone to being affected by crosswinds and maintaining a high rotor speed during take-off can reduce crosswind interference.



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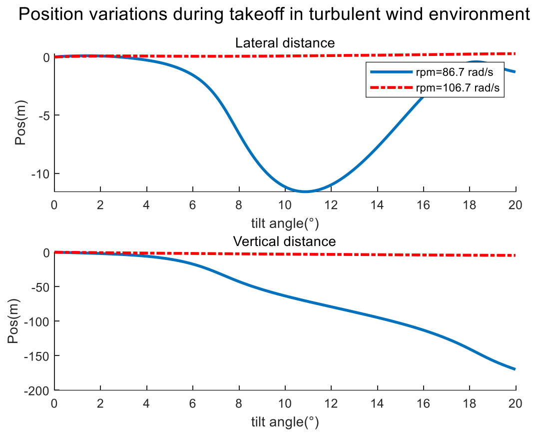

(b)

Figure 17: Parameters during takeoff process

5. CONCLUSIONS

Due to insufficient research on crosswind rejection strategies and crosswind-resistant design methodologies for vectored thrust eVTOL aircraft, this study employs flight simulation techniques to conduct a series of parametric influence analyses. The key conclusions are as follows:

1. eVTOL may enter unstable state due to the influence of crosswind with moderate wind speed during takeoff and landing stage, so it is necessary to consider the influence of crosswind during design.
2. The higher rotor speed enables eVTOL to maintain their stable posture more easily when encountering gusts.
3. Crosswinds are more likely to affect takeoff than landing.
4. Wing-down approach has a better anti-interference ability in crosswind conditions compared to crabbed approach.

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