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Survey of Research on Wind Resistance for Quadrotor UAVs

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Micro UAVs have been widely used in recent years because of their simple structure and convenient operation. However, due to under-actuated and strongly-coupled characteristics, their flight performance is not perfect when suffering external uncertainty such as wind disturbance. Therefore, in this paper, the literatures are reviewed related to wind acting on UAVs and make some conclusions. The topics include the general wind field models, wind disturbance influence mechanism and some control laws to improve the capability of wind resistance for UAVs. We review the promising works which have been done before, and determine the research emphasis to be focused on later.

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1. Introduction

Unmanned Aerial Vehicles (UAVs) were first introduced in the 1910s during WWI. After more than a century of development, especially in recent years, with the vigorous development of MEMS, new materials, micro-inertial navigation and flight control technology, these vehicles have been widely used in many applications such as security and protection, management of natural risks, delivery transportation, industrial and agricultural production, military defense and so on. Utilization of UAVs makes it possible to gather information more quickly and effectively without risk to flight crews. Quadrotor UAVs, as the representative of simple structure and convenient operation, is the most common structure style of UAVs in our daily life nowadays. Since its birth, the research on the quadrotor UAV has never stopped. Up to now, the research on the modeling and control of the quadrotor UAV has been quite abundant[1]-[3]. The general quadrotor can basically achieve automatic taking off and landing, fixed-point hovering, trajectory tracking and other capabilities. However, these techniques are usually subject to certain conditions on working environment, such as keeping a certain distance from buildings or not taking off or landing under the condition of excessive wind speed. Most of these conditions are derived from the uncertainties of flight environment, among which the influence of wind disturbance on UAVs is a part that can never be ignored. It is found that there are a few literatures focus on the quadrotor control under wind disturbance condition. The reason may be that most researchers directly focus on the control system to improve the wind resistance performance of UAVs, instead of analyzing the wind disturbance model and its influence mechanism to the UAVs. Generally, this method may be useful but cannot improve the capability of wind resistance of UAVs in principle. Micro-UAVs weighing less than 7 kg are the most common in our daily life. Therefore, this paper is set as the wind resistance control of quadrotor aircraft, hoping to conduct in-depth research on the wind field model under the common working environment of micro-UAVs, the influence mechanism of wind disturbance on UAVs and the controller design of quadrotor UAVs. For this reason, our studies are mainly divided into three categories: wind field modeling of UAV working environment will be introduced in Sec.2, Sec.3 will present the influence mechanism of wind disturbance on UAVs, and in Sec.4, wind resistance research and verification of flight control system will be introduced. Finally, conclusions will be discussed in Sec.5.

2. Wind field models in working environment

The study of wind field models was carried out very early, and it was mostly used in the military field in the early stage. In 1973, NASA and relative research institutions[4] began to study the wind disturbance model of the surface boundary layer, and put forward wind field models under stable and unstable conditions respectively. They made a great progress in wind field modeling, but did not compare with the actual flight conditions fully and were only studied in theory. Later in the 1980s, James R. S.[5] discussed the feasibility of three statistical methods in combination to establish the wind gusts model which was used in aircraft flight simulation. They combined principal components analysis, time-series analysis, and probability distribution methods to simulate and analyze wind gust components. Comparisons between wind gust components generated by this model and those measured onboard an aircraft showed that they were similar generally. B. Etkin[6] analyzed the basic model of turbulence and its influence on aircraft and E. L.

Fleming et al.[7] studied the relationship between the average temperature, air pressure, wind field and the altitude and latitude of the location. Most of the wind field models established above were based on large-scale space and time conditions. Different from this, wind field research under small-scale space and time conditions was also being carried out as well. The US military first introduced Dryden and Von Karman turbulence models in its military specifications[8], and most of the turbulence wind field models used later came from this. The Von Karman form of the power spectral densities for the turbulence velocities is as follows:

$$\begin{cases} \Phi_u(\Omega) = \sigma_u^2 \dfrac{2L_u}{\pi} \dfrac{1}{\left[1+\left(1.339L_u\Omega\right)^2\right]^{5/6}} \\ \Phi_v(\Omega) = \sigma_v^2 \dfrac{L_v}{\pi} \dfrac{1+(8/3)\left(1.339L_v\Omega\right)^2}{\left[1+\left(1.339L_v\Omega\right)^2\right]^{11/6}} \\ \Phi_w(\Omega) = \sigma_w^2 \dfrac{L_w}{\pi} \dfrac{1+(8/3)\left(1.339L_w\Omega\right)^2}{\left[1+\left(1.339L_w\Omega\right)^2\right]^{11/6}} \end{cases} \tag{1}$$

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where

u, v, w = velocities along x, y, z axes of aircraft, ft/s
Φ_u, Φ_v, Φ_w = power spectral of u, v, and w, ft^3/s^2
$\sigma_u, \sigma_v, \sigma_w$ = standard deviations of u, v, and w, ft/s
L_u, L_v, L_w = scale lengths for u, v, and w, ft

It can be verified by direct integration of each of the preceding spectral densities that

$$\sigma_{u,v,w}^2 = \int_0^\infty \Phi_{u,v,w}(\Omega)d\Omega \tag{3}$$

In 1993, Beal T. R[9] presented two algorithms which can generate discrete-time histories of random atmospheric turbulence as prescribed by the Dryden and Von Karman model. In fact, these two algorithms are the most widely used expressions of the turbulence wind filed. However, Since the time spectrum function of Von Karman model cannot be decomposed in conjugates, which is difficult to be realized in time domain, therefore the wind field turbulence generated by Dryden model is more often used in numerical simulation.

The earliest simulation analysis of atmospheric turbulence model in China can be found in literature [10] and [11]. In 1986, Professor Zhao et al. proposed a strict and complete three-dimensional atmospheric turbulence signal including three linear velocity components and three angular velocity components in line with Dryden's model, and verified the reliability of the results with the correlation function. Later, other researchers [12]-[14] proposed improved methods on this basis, in which Xiao[12] for example, generated two-dimensional field of turbulent for special situations such as formation flight and aerial refueling. The correlation of so generated turbulent field was found to be in good agreement with the theoretical correlation of Dryden model, thus the feasibility of the proposed method was verified. Since the correlation function of Dryden model was not quite consistent with the theoretical value in some case, Ma[13] theoretically analyzed the causes of the error, and put forward the corresponding improvement method. The improved simulation results verified its great performance. After comparing the differences of power spectrum between Dryden model and Von Karman model, Qu et al.[14] proposed a form of improved turbulence model by optimizing its parameters. The simulation results in time and frequency domain showed that the proposed new model was rational and the suggested simulation algorithm was valid. This new atmospheric turbulence model and its simulation algorithm can be used both in the real time and non-real time digital simulation calculation for flight dynamic systems. The above studies were aimed at the atmospheric turbulence as a typical wind field model acting on full-size aircraft, while the actual wind field often has other typical wind field models, such as constant wind model, wind shear model and so on.

In order to improve the precision of the wind filed model comparing with actual environment, other typical wind models had been proposed besides turbulence wind model. Cole et al.[15] introduced a statistical wind model over water which was different from traditional gust wind models such as Dryden or Von Karman models. They tested the different impacts on quadrotor under three wind conditions (mean wind speed=1, 5, and 10m/s). Simon Watkin et al.[16][17] mainly focused on the problem how to establish the disturbance atmosphere boundary layer, particularly disturbance a few meters above the ground. They considered the temporal and spatial characteristics of the atmospheric boundary layer near the ground, as well as the relative disturbance experienced by the moving aircraft. Then several highly accurate pressure sensors were used to measure and calculate the variation of the wind speed, and the transient and time-averaged velocity of the wind at a height of 4 meters above the ground were described. Finally, they tried to reproduce the typical atmospheric disturbance in the wind tunnel. The results showed that the established simulation model was in identical with the actual measured wind field model and the wind tunnel test showed a high similarity with the atmospheric disturbance data measured. Mann[18][19] developed a model of the spectral velocity-tensor in neutral flow over complex terrain by measuring the real-time changing wind speed and direction. Compare with the Sandia method[20], this method is more efficient, simpler to be implemented, and more meaningful physically in some respects. Branlard[21] proposed a time series wind model based on Kaimal spectrum, and the FFT results of the wind speed generated by the model were in good agreement with Kaimal spectrum. Four different 10-minutes samples at 10Hz generated from this method are displayed on Fig. 1. Their mean values are exactly 20 m/s, whereas their standard deviations vary between 0.90 and1.23 m/s. The samples resemble quite well with real wind time series. This wind field model was then used by Nikola G.[22] for the simulation of UAV under the influence of wind disturbance, and relatively ideal results were obtained.

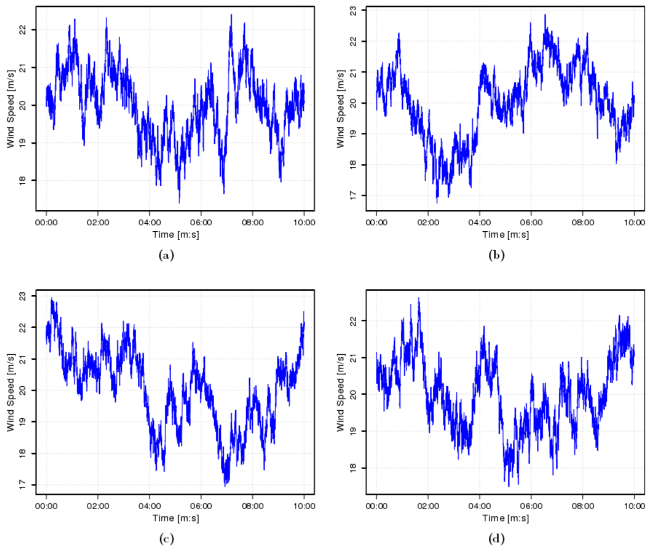

Fig. 1. Four examples of time series generated from the Kaimal spectrum.[20]

The actual wind field model of UAV is usually not a single wind field, but the superposition of many typical wind fields. In 2009, Yu[23] introduced the model of wind shear and atmosphere turbulent in his academic dissertation. He described in detail the mechanism of these two wind fields and tested the corresponding action of aircraft under wind disturbance. Simulation results showed that the wind models introduced were ideal and valid. Similarly, Waslander[24] also considered the wind disturbance as a superposition of the wind shear model and Dryden turbulent model. It was verified by the simulation results that the wind disturbance data generated by the above wind field model was in good agreement with the actual wind disturbance. Later Wang[25] and Christian Mansson[26] pointed out that the usual wind field where UAV works is a superposition of constant wind model, wind shear model and Dryden turbulent model. Furthermore, Wang[27] considered the wind field model as a combination with constant wind, turbulent wind, many kinds of wind shear, and the propeller vortex which can be presented as below:

$$V_w = V_c + V_t + V_s + V_v \tag{4}$$

where

V_w = combination of wind speed vector
V_c = constant wind speed vector
V_t = turbulent wind vector
V_s = shear wind speed vector
V_v = weak vortex effect wind vector

Except for the fourth wind model, which is generally considered in UAV formation flight, the other three wind types are all typical wind field models. This classification method is also the most common one to decompose wind field models at present. Behdad Davoudi et al.[28] tried to combine large-scale spatiotemporal wind field model with small-scale spatio-temporal wind field model. Large-scale spatial and temporal wind field models include Large-eddy simulation, the approximate solution of the Navier-Stokes equations, and its reduced-order wind representations, while the Dryden turbulence model belongs to small-scale spatial and temporal model. MATLAB simulation results showed that the models were consistent with actual environment, but there were still some difficulties in modeling the large-scale spatiotemporal wind field.

As can be seen from the above literatures, the wind field modeling for the working environment of the UAV has been relatively complete. In order to facilitate users to add wind disturbance to the simulation, MATLAB, one of the most commonly used software for numerical simulation, has packaged several typical wind field models into modules according to relevant standards. Users can call them directly from library, just need to adjust some parameters in the set interface.

3. Research about influence mechanism of wind

Understanding the intrinsic mechanism of wind acting on aircraft helps build accurate mathematical models and a simulation environment which helps to verify whether the controller proposed has the ability to reject the wind disturbance. Considering the influence of wind disturbance on UAVs, it can be divided into two parts: one is the effect of wind disturbance on the rotors, and the other is the effect on the fuselage. The former mainly discuss the influence of wind disturbance on a single rotor and extend to multi-rotor as well. Due to the influence of wind disturbance on speed and downwash airflow, the force and torque generated by the rotating blade will changed, so as change the overall stress condition of UAVs. The latter usually treat the UAV as an entity and analyze the drag and torque effect of wind disturbance on it.

In order to fully understand the influence of wind disturbance on rotors, we need to introduced the induced velocity generated by rotating rotor. As early as 1926, in order to solve the difference between experimental observation and theoretical calculation of rotor lateral forces caused by uniform inflow, Glauert[29] proposed a first-order harmonic inhomogeneous inflow model that generated the induced velocity field. The theory was developed on the assumption that the angles of the blade elements were small, that the interference flow was similar to that caused by an ordinary aerofoil. With the comparison of calculated and experimented results, Wheatly et al.[30] made a conclusion that most of the rotor characteristics could be calculated with reasonable accuracy, and that the type of induced flow assumed had a secondary effect upon the net rotor forces, although the flapping motion was influenced appreciably. In order to further understand the induced velocity of the rotor disk, in 1945, Coleman[31] proposed a formula for the normal component of induced velocity along the fore-and-aft diameter of the rotor disk using a concept of a simplified vortex system of a rotor wake. A comparison of the theory with corresponding values of induced velocities computed by Seibel's formula was taken as evidence that the most significant factors had been taken into account and the result was reasonable. In 1947, Brotherhood[32] measured the induced velocity distribution of UAV in hovering state. Results showed that measured value of the induced velocity had a great correlation with the calculated value of blade element theory. Later, experiments had been made to determine the flow conditions through a helicopter rotor in forward flight using the smoke filament technique by Brotherhood and Steward[33]. However, the induced velocity measured by them was quite different from the results obtained by Mangler and Square[34] based on potential theory. Before 1950s, the influence of static and time-invariant incoming flow on the induced velocity of rotor was mainly concerned. Till 1953, an experimental determination of the response of the thrust and induced velocity of a helicopter rotor to various rates of collective blade-pitch increase had been conducted on the langley helicopter test tower by Carpenter and Fridovich[35]. The calculated and experimental results were in agreement generally, although, the former were about 10 percent greater than the latter.

Later with the emergence of electronic computers and the improvement of computational performance, researchers have been able to obtain a large number of experimental data and then analyze complex mathematical formulas and verify them by comparison with experimental data. In 1972, Harris[36] published a series of low-speed blade data obtained from wind tunnel tests. He used various static inflow models to calculate theoretical flapping angles and compared them with experimental data. Later, he made a conclusion that none of the existing models could well predict rotor flapping angles. Then by tuning the parameters of the optimization model, Johnson[37] was able to make the lateral flap-wise calculated well consistent with the experimental data of Harris, which filled in the shortcomings of Harris's work. Recently in 2015, W. Khan[38] analyzed the magnitude and distribution of induced velocity generated by rotor rotation in detail from the perspective of Blade Element Momentum Theory (BEMT), and established corresponding mathematical models respectively for the conditions of with or without wind disturbance. The simulation results showed that the model can well reproduce the wind effect of a single rotor. Laura E. M[39] and Wu[40] et al. supposed that the contact surface of the body aircraft and the crosswind is very small thus the force produced by the wind in this surface is also tiny which can be neglected. For UAVs with propellers, it is believed that the airflow generated by the propellers would be affected by the lateral wind inevitably and introduce additional forces on the aircraft. The magnitude of these forces depends on the velocity of the induced wind of the propeller and the incoming lateral wind. They superposed the lateral wind airflow and the downwash airflow, and then the force generated by the rotor was obtained by the known parameters of air density and effective area of the propeller disc. Pretty simple and easy to calculate it is, but this method has a big error with actual situation. Behdad Davoudi et al.[28] established the model of rotor force and torque and the quadrotor mode under wind disturbance effect based on the momentum and blade element theories introduced by Leishman[41]. This model analyzes the effects of rotor action and wind disturbance on quadrotor from a theoretical point of view, which requires higher knowledge of aerodynamics and mechanical structure. In the process of modeling, it is necessary to accurately measure the object and process a large amount of data to ensure the accuracy of the model.

Above references mainly talk about the influence from wind disturbance to single rotor. In 2007, Hoffmann et al.[42] were one of the first to consider aerodynamic effects into the model of the quadrotor. They explored the resulting forces and moments applied to the vehicle through the aerodynamic effects and investigated their impact on quadrotor attitude and altitude. The results have shown that existing models and controllers were inadequate for accurate trajectory tracking in uncontrolled environments. Bangura and Mahony[43] were among the first who try to give a detailed explanation of all aerodynamic effects affecting the quadrotors dynamics. They considered in detail several aspects, such as blade flapping, induced drag, translational drag, profile drag, parasitic drag and also others such as ground effect and vertical descent. In the quadrotor model proposed by Allibert et al.[44], translational drag and blade flapping are considered bilinearly influenced by the thrust and the horizontal velocity relative to the wind. They neglected parasitic drag since the quadrotor operated near hovering state. Moreover, they also considered the vertical thrust force variation due to the induced velocity generated by rotors. Nguyen et al.[45] believed the effect of wind on the motion of a quadrotor is partially caused by the drag of the quadrotor fuselage, and partly due to the interaction between the propellers and the wind. They established the propellers model under wind disturbance by referring to Khan's work[38], and calculated the drag coefficient by measuring the drag force acting on a quadrotor in the given cross airflow. Moreover, considering that not all of the propellers were directly exposed to the wind, they introduced the shielding effect, which represented by a weighting function.

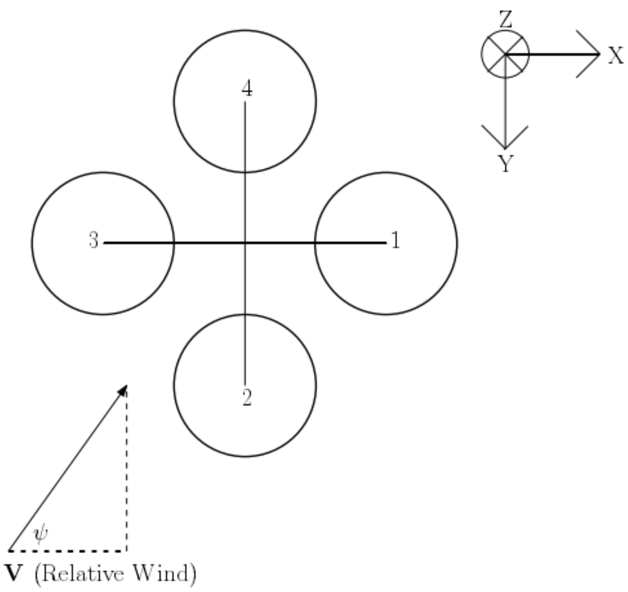

Fig. 2. Wind shielding effect[38]

As shown in the Fig. 2, rotor No.2 and No.3 are more affected by the wind disturbance than No.1 and No.4. We believe their ideas are meaningful, but this method was oversimplified. The value about weight function of shielding effect should be determined carefully instead of setting as a constant value. In 2012, Mahony et al.[2] pointed out that blade flapping and induced drag are of significant importance in understanding the natural stability of quadrotor. Base on this, they modelled a general quadrotor with great precision. Besides in 2015, Ryll et al.[46] took the aerodynamic effects into consideration and set the appropriate experiment to obtain the model corresponding coefficients. Based on their work, it was shown that the aerodynamic effects can be neglected. They also considered the induced drag and blade flapping as first-order dynamic effects but still neglect them. However, the experimental condition they set was not clearly adequate with the wind speed less than 1 m/s. Actually, winds of around 4 m/s are very common and called as gentle breeze. Later in 2018, Silva et al.[47] introduced several aerodynamic effects such as blade flapping, induced drag and parasitic drag into quadrotor dynamics and the method of parameter identification is also given. Experimental results proved that the model was accurate.

Considering the impact of wind disturbance on the UAVs fuselage, Yongling He et al.[48] established a quadrotor dynamic model under wind field based on Newton-Euler formalism. Similarly, Tang et al.[49] only analyzed the influence of wind disturbance on the quadrotor UAV from the perspective of force. They considered the quadrotor model as a rectangular body, and selected the front, side and top of the quadrotor to calculate the windward area. The relative airspeed could be obtained from the wind speed and the ground speed of the aircraft. Finally, the effect of wind on the overall force of the quadrotor UAV was obtained through acknowledged parameters such as aerodynamic coefficient and air density. In 2014, some simplifications, about how the projected surface area of aircraft is calculated from an arbitrary point of view, were presented by Christian Mansson and Daniel Stenberg[26]. This way, they may not be exactly correct, but at least an approximation was provided where the horizontal and vertical dimensions of the vehicle are given some representative relevance in regards to the winds direction. The traditional aerodynamic model of the quadrotor is almost entirely based on the modeling of a single rotor, ignoring the wake interference among the four rotors in close proximity. As a consequence, in traditional quadrotor models, four rotors are all alike with the same thrust force, moment, drag force and other aerodynamic effect. In order to control the attitude and position of the quadrotor accurately and effectively, in 2015, Luo et al.[50] proposed a quadrotor forward-flight mathematical model considering rotor wake mutual interference. To validate the precision of the model, a series of Computational Fluid Dynamics (CFD) analyses were conducted. An integral quadrotor model and an isolated rotor were analyzed under the same conditions. The mathematical model and results of the CFD analyses provided consistent trends and demonstrated the suitability of the proposed model for high-speed forward flight. In 2019 and 2020, Wang et al.[27][51] also carried out research on the impact of wind disturbance on UAVs. Compared with the previous literatures which mostly only considered the speed triangle theory and air drag, this paper analyzed the impact of wind disturbance on UAVs from the perspective of energy transfer referring other literatures[52]. Based on the conservation of energy and momentum theory, the velocity variation of UAVs under wind disturbance can be deduced. With this simple and understandable analysis method, its simulation results showed that the results obtained from the perspective of energy transfer are more consistent with the actual situation than other analysis methods. In 2020, Jeremie et al.[53] tried to establish an accurate quadrotor model under wind disturbance filling the gap between simple models that ignore important aerodynamic effects and other more comprehensive but computationally expensive models. They first measured the constant wind interference effects on quadrotor model, get the mathematical relationship between force and moment applied to the drone and wind direction and velocity. Then the quadrotor model was optimized and the parameters were tuned. Finally, the simulation model data was compared with the measured data of the quadrotor under the influence of wind tunnel. Results showed that they were in good agreement, which proved the rationality of the quadrotor model under the influence of wind disturbance. However, the wind disturbance added in simulation and tunnel test were constant, which is different from actual outdoor environment. Therefore, there are still some areas to be improved. In Lei's paper[54], the aerodynamic characteristics of a quadrotor aircraft considering the wind disturbance were studied by both simulations and experiments. The comparison of simulation and experimental results showed that the distribution of flow field becomes more complicated with mutual interferences resulted by the distortion of rotor wake and crash of the downwash flow from the front rotors along with the wind direction. However, they only considered the constant horizontal wind disturbance, ignoring the role of turbulent wind field, so the model was limited.

In almost all the literatures above, when considering the influence of wind disturbance on the whole UAV, only the force generated by wind disturbance on the linear velocity of UAV is analyzed while the torque generated by the wind on the angular velocity is ignored. However, the characteristics of the quadrotor itself mean that this influence cannot be ignored. Additionally, if the down washing airflow generated by rotor rotation is considered to be affected by the wind disturbance, additional force will be generated, and if the direction of this force does not pass through the quadrotor center of gravity, the torque effect will occur, which is also a non-negligible factor to be considered in modeling.

Over all, the effect of wind disturbance on quadrotor aircraft is not a simple linear or simple-input simple-output relationship, but there are a lot of uncertainties. It is necessary to carry out this study form various of aspects, compare the theorical results, simulation results and actual experimental results together, and get the accurate mathematical quadrotor model under wind disturbance finally.

4. Research on controller design for wind resistance

There are lots of literatures about flight control design for quadrotor aircraft, which quality are uneven. Proportional-Integral-Derivative (PID) control law, as the most basic and traditional control law, accounts for more than 80% of the control system applications, and has been widely used in the quadrotor flight control system. However, subject to quadrotors' complex aerodynamic effect, under-actuation, strong coupling and other characteristics, it is hard to design an appropriate controller to maintain good performance of the quadrotor. When considering the outdoor flight tests with wind disturbance, it is a more challenge condition which has a lot of uncertainties.

In 2004, Bouabdallah et al.[55] used the traditional PID control law and Linear Quadratic Regulator (LQR) to control the quadrotor. They were first tested in a simulated environment, followed by bench experiments and finally real flight tests were showed. Due to the rough sensor data processing and unreasonable controller design and parameter tuning, the experimental results were not ideal, but it can still prove the feasibility of PID and LQR controller. Then they designed an attitude controller for OS4 micro-quadrotor with backstepping and sliding-mode algorithm[56]. As it can be seen from the experimental results, the controller using the sliding-mode approach provided average results while the backstepping controller proved the ability to control the orientation angles in the presence of a relatively high perturbations. The quadrotor model composed of translational and rotational subsystems was dynamically unstable and nonlinear, so a sequential nonlinear control strategy was used by Mian et al.[57]. The control structure included feedback linearization coupled with a PD controller for the translational subsystem and a backstepping-based PID nonlinear controller for the rotational subsystem of the quadrotor. The performances of the nonlinear control method were evaluated by real-time simulation and the results demonstrated the effectiveness of the proposed control strategy for the quadrotor helicopter in quasi-stationary flights state. Daewon Lee et al.[58] presented two types of nonlinear controllers for an autonomous quadrotor helicopter. One is a feedback linearization controller involved high-order derivative terms and turned out to be quite sensitive to sensor noise as well as model uncertainty. The second type involved an adaptive sliding mode controller using input augmentation in order to account for the under-actuated property of the quadrotor, sensor noise, and uncertainty without using control inputs of large magnitude. The adaptive sliding mode controller performed very well under noisy conditions, and can effectively estimate uncertainty such as ground effects. Similarly, Nonlinear PID controller was proposed to control the quadrotor UAV by A. B. Milhim[1] in 2010. A series of trajectories were used to demonstrate the effectiveness of the designed controller. It can be seen from the Fig. 3 that the proposed control method can realize UAV position control effectively, and the robustness and capability of disturbance rejection were improved.

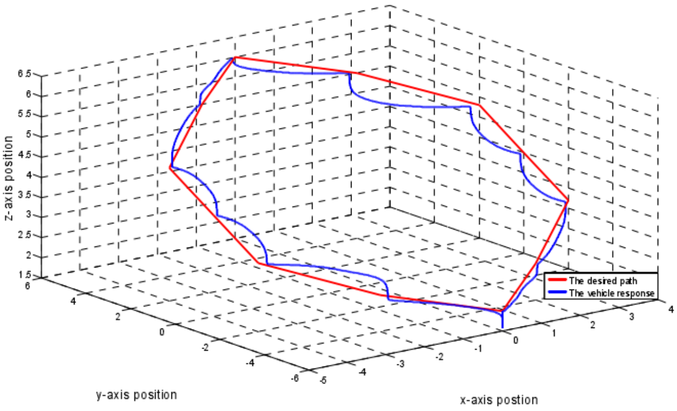

Fig. 3. Trajectory tracking for the vehicle in three dimensional view[1]

In the actual flight condition, for quadrotor flying at low altitude, it is more susceptible to wind field that could significantly affect the aerodynamic performance and its stability. Therefore, it is necessary to take the impact of wind field into account in the study of quadrotor system's modeling and control[59]. To overcome this problem, there have been a few researches about improving the performance of quadrotor in wind field recently. Some specialists introduced various control laws to improve the wind resistance capability of quadrotors.

In 2009, Guowei Cai et al.[60] designed and implement a robust automatic flight control system for a small-scale unmanned helicopter. Based on helicopter's linearized model, a robust automatic flight control system was designed by employing H_∞ control and dynamic inversion techniques. The simulation and actual flight experimental results showed that their designed controller was very successful and had the capability to resist wind disturbance at least 4m/s. Yanmin Chen et al.[59] introduced their promising work in 2013. In their study, a dynamic model of the quadrotor considering the influence of wind field was established firstly. Then their designed a nonlinear integral backstepping controller and validate the stability of the system by Lyapunov theory. Simulation results demonstrated that the model can reflects dynamic performance of the system under wind disturbance but the control performance was not much better than traditional controllers, such as PID. Therefore, this work continues. The next year, Kooksun et al.[61] presented a robust attitude tracking controller for quadrotors based on the nonlinear disturbance observer. It is showed the proposed controller recovers the performance of the nominal closed-loop system under parameter uncertainties and disturbance torques. In view of the influence of wind disturbance on UAV track tracking, Stephen Jackson et al.[62][63] proposed a random optimization method based on training set, and then designed a spatial sliding mode controller and a receding-horizon kinodynamic controller. Hardware in the loop simulation and real flight experiments showed that the controllers were able to follow the path of UAVs well under external disturbance. However, the controllers mentioned were designed for fixed-wing UAVs, which are quite different from multi-rotor aircraft. In 2008, Azinheir and Moutinho et al.[64] presented a backstepping-based controller with input saturations, applicable for the hover flight state of UAV. Simulation results were presented for the hover stabilization of the UAV, which were demonstrative of the excellent performance of the proposed controller and proved its capability of disturbance rejection in the face of wind disturbance. In 2009, in order to solve the path following problem for a quadrotor helicopter, Raffo G. V. et al.[65] introduced an integral predictive and nonlinear robust control strategy. The proposed control structure was a hierarchical scheme consisting of a model predictive controller (MPC) to track the reference trajectory together with a nonlinear H_∞ controller to stabilize the quadrotor helicopter. In both controllers the integral of the position error was considered, requiring the achievement of a null steady-state error when sustained disturbance were acting on the quadrotor flight system. Simulation results in the presence of aerodynamic disturbances, parametric and structural uncertainties, were presented to corroborate the effectiveness and the robustness of the proposed control strategy. An embedded robust nonlinear controller to stabilize a quadrotor aircraft under crosswind disturbance was developed by L. E. Munoz et al.[39] in 2011. The stability analysis and robustness with external disturbances was proved using the Lyapunov theory. Simulations had been accomplished to validate the performance of the proposed control schema. Additionally, a prototype with an embedded control system was created to prove, in real-time, the effectiveness and robustness of the proposed algorithm. Experimental results had illustrated the good performance of the closed-loop system even in presence of wind disturbances. Kostas Alexis and his team[66][67] studied the attitude and position control of the quadrotor UAV affected by wind disturbance with Constrained Finite Time Optimal Controller (CFTOC). Simulation and real flight experiment results showed that this scheme was an effective control approach, capable of effectively attenuating strong wind disturbance. The presented experimental results indicated the efficiency of the proposed controller both in attitude setpoint control and wind gust disturbances resistance. For example, it can be seen from Fig. 4 that wind disturbance will have a serious impact on the angular rate of the quadrotor but in Fig. 5 and Fig. 6 under the action of the controller proposed, the attitude can still be well controlled.

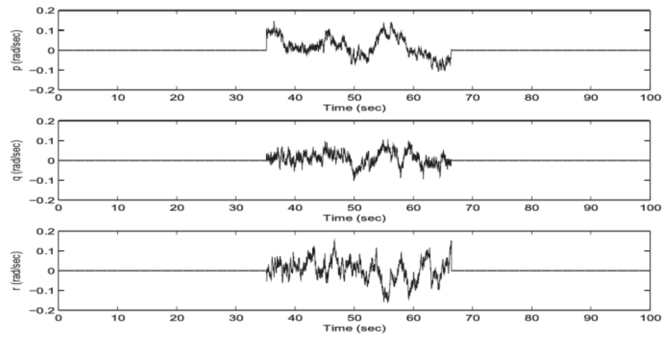

Fig. 4. Corresponding rotational rates disturbance caused by the wind disturbance[66]

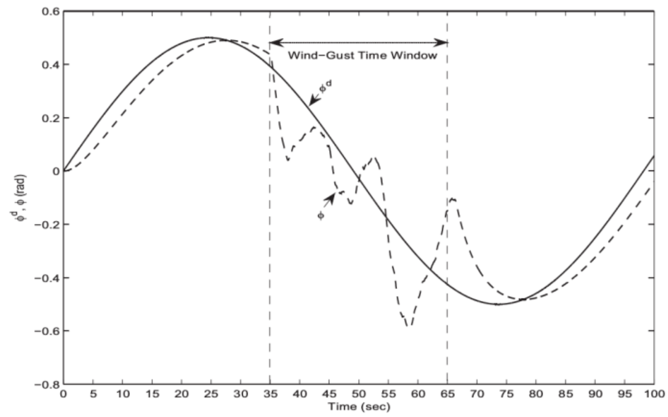

Fig. 5. Tracking response of the roll angle($\boldsymbol{\phi}$) under wind-gust disturbance[66]

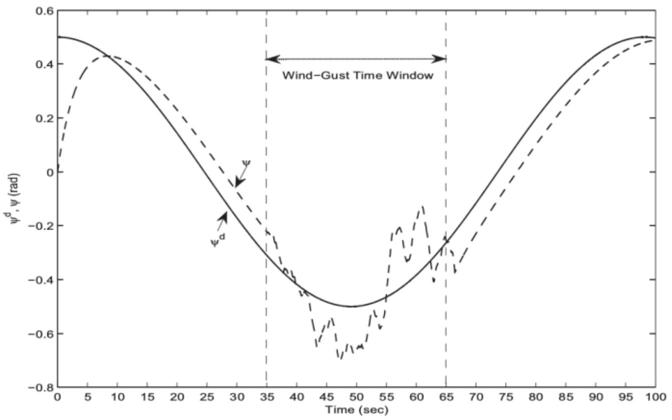

Fig. 6. Tracking response of the yaw angle($\boldsymbol{\psi}$) under wind-gust disturbance[66]

In 2013, a quadrotor position controller was designed by He et al.[48] included integral backstepping controller for inner loop and PID controller for outer loop. The dynamic performance and control ability under the effect of turbulent wind were studied with numerical simulation. The results showed the controller had a good robustness and disturbance resistance in the effect of wind disturbance. Nguyen Khoi Tran et al.[45] designed the attitude controller for quadrotor model under wind disturbance. Firstly, PID and LQR control laws were used to design the controller. Then, in order to improve the anti-disturbance performance of the control system, some improvements were made on the basis of the traditional LQR control law adding integration element. The simulation results showed that the improved LQR control law enhances the disturbance rejection performance of quadrotor, but the LQR control law needs an accurate mathematical model of the controlled object, but it is difficult to obtain the corresponding model of the quadrotor. In order to enhance the wind rejection ability of UAVs to achieve safe and precision control, a wind disturbance rejection control method based on acceleration feedback (AF) was proposed for multirotor UAVs by Dai Bo et al.[68] in 2020. By introducing linear and angular acceleration information feedback into the original controller, a faster and more accurate attitude and position tracking performance can be obtained without changed the structure of the original controller. In Fig. 7, traditional PID controller was used between 180s-240s and acceleration feedback was introduced after 240s. The experimental results demonstrated that the acceleration feedback enhanced controller can suppress the turbulent wind effectively and the accuracy of UAV flight control system was greatly improved.

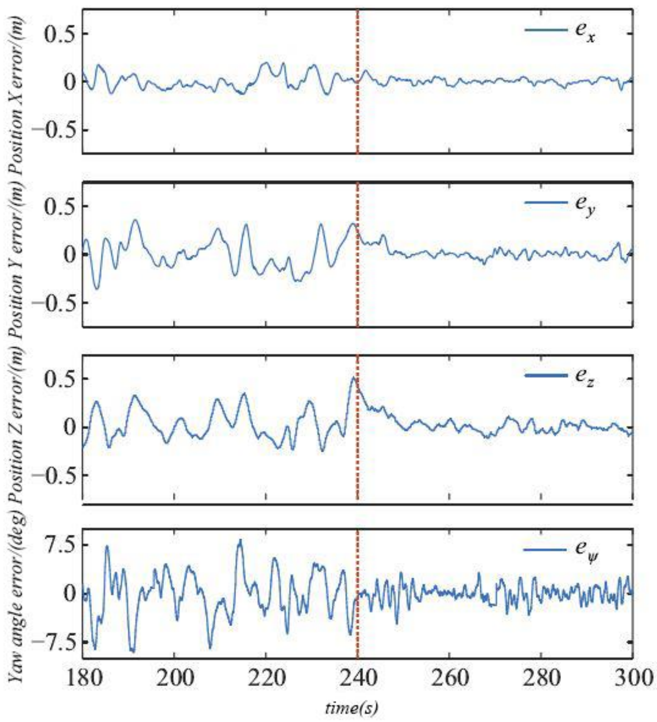

Fig. 7. Position and yaw tracking errors of the hex-rotor under continuous wind disturbance[68]

In the above studies, the control strategies adopted resist wind effect in a passive manner for the UAVs. In other words, when the wind disturbance has a great influence on the position and attitude of the UAV and deviates from its reference position and attitude, the corresponding control value is calculated accordingly to reject the wind disturbance effect. Objectively, the passive control strategy will produce a large control delay and may appear the phenomenon of oscillation, so a lot of experts consider how can the controller include the wind influence, instead of only considering it as a disturbance to be further rejected. We call this type of new methods as active wind resistance strategy, which has been the first choice to realize the effective anti-wind for UAVs.

In 2009, Waslander et al.[24] used the traditional PID controller and the improved PID controller with acceleration constraint to improve the precision of position control of quadrotor under wind disturbance. The control system estimated the wind disturbance of the environment and took the initiative to resist the wind according to the wind speed and direction information. Simulation results showed that the improved PID controller has better robustness under wind disturbance. Similarly, Nitin Sydney et al.[69] designed the quadrotor controller based on wind field estimation as well. They used the recursive Bayesian filter to estimate the wind field, which was incorporated into an input/output feedback linearization controller that included aerodynamic effects on the vehicle such as blade flapping and induce drag. It was evident through simulation results that the inclusion of the airflow compensation in the controller design enhance the ability of quadrotors to perform simple control objectives. Qu et al.[70] designed a PID controller with a similar idea to maintain the hovering state of the quadrotor. Based on the pose information of the quadrotor in the hovering state, the wind field environment information of the aircraft can be calculated. MATLAB simulation results showed that this method can effectively extract the information of the main wind in the wind field environment with turbulence. In 2019, Tang Liang et al.[49] designed a position controller for quadrotor under the impact of wind disturbance. In the process controller designed, the extended state observer (ESO) was used to estimate and compensate the total disturbance in real time, and combined the double power reaching law for sliding mode control (DSMC) with small chattering and fast response speed. By performing closed-loop stability analysis on the controller, ESO-DSMC converges in a fixed time. The simulation results proved that the position optimization law of the proposed control law can reach about 90% under wind disturbance, which improved the anti-interference ability and robustness of the system.

Active Disturbance Rejection Control (ADRC), as a control law which is similar to PID Control which does not depend on the precise mathematical model, has become an effective tool to study the nonlinear system once proposed. ADRC is proposed for systems with big internal and external uncertainties. It can not only achieve accurate control effect, but also has a great ability of robustness and disturbance rejection. The idea this control law takes is to regard the external disturbance and internal uncertainty of the system as the "total disturbance", and use the ESO to estimate and compensate this disturbance in real time. In view of the internal uncertainties (parameter uncertainties or unmodeled dynamics) and external disturbance (change of flight environment, atmospheric disturbance, etc.) existing in the quadrotor UAV system, the UAV control system must have a certain comprehensive disturbance rejection capability, so the ADRC control law has a great advantage. Many experts have studied the application of ADRC in the field of UAV control.

In 2009, Hua Xiong et al.[71] designed an automatic takeoff control system based on the ADRC. Comparing with previous methods, their approach can directly and real-timely estimate the UAV's internal and external disturbances and then compensate for them. Simulation results showed that their automatic takeoff system can lead the UAV to takeoff safely under wide range wind disturbances (e.g., downburst, wind turbulence). In 2016, Wu[40] designed the quadrotor flight controllers based on PD and ADRC control laws in his graduation thesis. It can be seen from the results that the designed PD controller can meet the requirements of the stability and rapidity of the control system without the wind disturbance, and can track the reference state well. However, when the wind disturbance appears, the PD controller had a poor rejection capability on the oscillation caused by the turbulent. Compared with PD controller, ADRC-based controller has better control performance and can effectively control the influence of the disturbance of the turbulent wind field. However, ADRC controller also has the problem of too many parameters to be tuned. In order to simplify parameter tuning of ADRC controller, the linear active disturbance rejection controller (LADRC) and fuzzy active disturbance rejection controller (Fuzzy-ADRC) were proposed in Bao's master's thesis[72], which refer to Han and Gao's[73]-[75] literatures. Controller design process and simulation results showed that the designed LADRC controller parameter tuning was easier comparing with nonlinear ADRC and the rationality and validity of the designed controller were tested. In the actual application of ADRC controller, there are also problems of poor adaptability of state error feedback control law, and low estimation accuracy of "disturbance" and poor compensation effect of extended state observer with fixed parameters. Wang[76] combined fuzzy control, neural network control and nonlinear ADRC to design the fuzzy ADRC flight control system and neural network ADRC flight control system. The feasibility of the control method was verified by indoor semi-physical simulation platform and outdoor flight platform. In 2018, Yang et al.[77] designed a closed-loop framework for quadrotor flight control law in wind field. In their work, ADRC and PD control were used in the inner and outer loops, respectively. The perturbations of gust wind were considered as one of the external disturbances, which were estimated by ESO in the inner loop. Comparing between Fig. 8 and Fig. 9 which using different control laws, the proposed control method for quadrotor has better performance under the effect of wind disturbance.

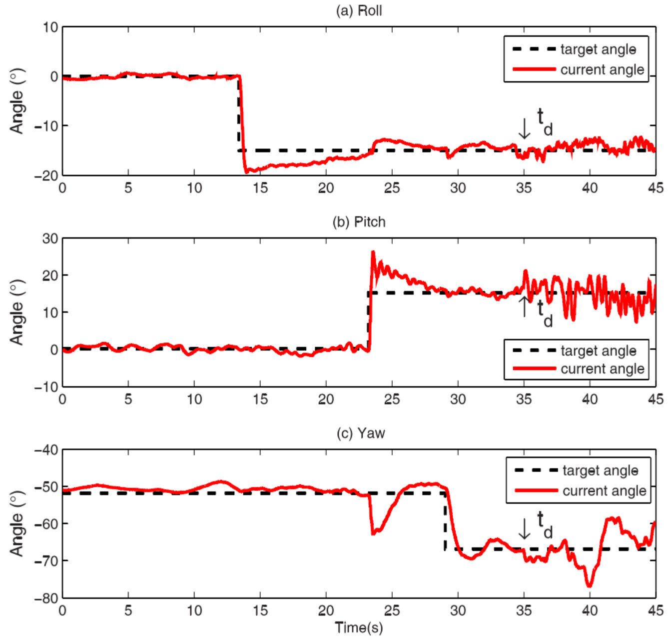

Fig. 8. 3DoF experimental results with the dual closed-loop PID controller[77]

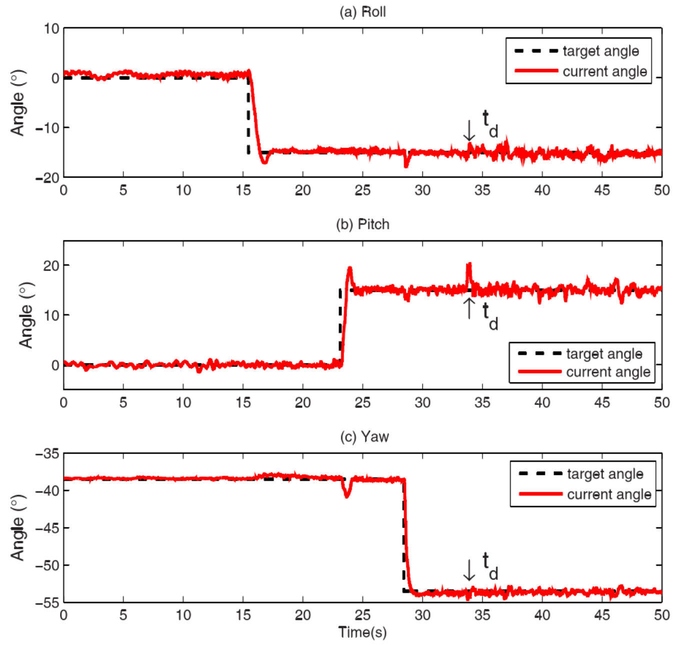

Fig. 9. 3DoF experimental results with the ADRC and PID controller[77]

From the above progress on wind resistance control law, it can be found that passive wind resistance control law has been gradually abandoned due to its large time delay and prone to oscillation and other reasons. In recent years, most studies have focused on the design and application of active wind resistance control law. Compared with passive wind resistance, it has many advantages, such as timely estimation and compensation of disturbance, strong disturbance resistance performance, etc., but it also has disadvantages, such as the controller parameter tuning is difficult, the frequent change of control quantity is unfavorable to the actuator, which should be paid more attention in the following research.

5. Conclusion

Research on wind resistance of quadrotor unmanned aerial vehicles (UAVs) originates from practical flight needs. Since its birth, great progress has been made in wind field modeling, wind disturbance influence mechanism on UAVs and wind resistance controller design. The established wind field model is more consistent with the actual environment, which is convenient for expects to simulate the wind disturbance conditions in the simulation environment. The influence mechanism of wind disturbance on UAV is basically clear, which provides necessary conditions for the subsequent establishment of accurate mathematical model of aircraft and the design of corresponding controller accordingly. In order to improve the anti-disturbance performance of the control system, the design of rejection wind disturbance controller changed from the passive anti-wind method to the active anti-wind control method adopted by the mainstream.

To sum up, great progress has been made in the study of wind resistance of unmanned aerial vehicles, and it is still progressing steadily. The main follow-up work will be to conduct the flight test from simulation to the actual physical flight platform.

Acknowledgments

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