

Research On the Mechanical Operation Principle of Uavs Based on Aerodynamics and Control Strategies

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Abstract. To address current UAV mechanical operation research focusing on ideal environments and poor adaptability to complex scenarios, this paper studies UAV mechanical mechanisms in complex environments to improve relevant theories and harsh environment adaptability. It reviews aerodynamics and control algorithms, then builds a coupled model linking lift/drag formulas with PID parameters, verifying its validity (lift/drag prediction error mostly <5%). Experiments in strong wind (0-15 m/s), rain/snow (moderate rain 10-25 mm/h, light snow 2.5-5 mm/h), and low temperature/pressure (-10-0°C, 80-90 kPa) show crosswind causes more lift loss (30% at 15 m/s) than headwind, snow impacts stability more than rain, and low temperature/pressure reduces lift by 15% with PID delay. The model enables reliable prediction for harsh-environment UAV design. Limitations and future directions (snow accumulation model improvement, practical verification) are noted.

Keywords: Mechanical operation principle; Aerodynamics; PID control; Coupling model; Complex environment.

1. Introduction

Unmanned Aerial Vehicles (UAVs), used to be mostly limited to military uses—now they've spread into all sorts of civilian areas, changing how whole industries work thanks to how flexible and efficient they are. Take aerial photography, for example: they snap good landscape shots and detailed photos of buildings, the kind of images that used to only be possible with costly manned planes. In logistics, they put medical supplies to remote mountain villages where there aren't many roads, and that saved a lot of time. And in agriculture, They sprayed pesticides on the farmland and observed the growth of the crops. Every time a UAV takes off smoothly and finishes its job safely, it's all because its mechanical operating system stays stable. The rotor blades can generate lift, helping the aircraft counteract air resistance and allowing the control system to adjust the flight posture of the unmanned aircraft. If the adjustment is not done properly, the unmanned aircraft may shake in the air, lose control when the wind force increases, and even crash, endangering the safety of the surrounding area.

In recent years, researchers from all over the world have done a lot of work on the mechanical operating principles of UAVs—and what they've found has given UAV development a really solid base to build on.

Take aerodynamics first: back in 2020, Smith and their team zeroed in on how UAV rotors produce lift [1]. They used the Bernoulli equation as their main tool, put together a math model, and figured out how lift changes when the rotor's speed or size shifts. What they found was helpful for designing rotors, but there's a catch—they only tested things in perfect conditions: no wind, no rain, just a quiet lab with nothing messing things up.

Then there's the side of control strategies. In 2021, Wang and colleagues came up with a PID control method to adjust a UAV's attitude [2]. When the UAV tilted a little, their algorithm fixed its position fast—keeping the error under 2% when the environment was steady. But when they tested it in winds that hit 8 m/s or stronger? The error shot up to over 10%. Why? Because the algorithm didn't factor in how wind changes the forces acting on the UAV's body.

Li and the team tried to fix that in 2022 [3]. They used model predictive control, which guesses what the UAV will do next so it can adjust controls ahead of time. But their model left out stuff like

snow sticking to the rotors or low air pressure at high heights. That means it's basically useless when the weather gets bad. All these studies have their good points, but they all have the same big problem: they don't fully take into account the real-world situations UAVs deal with every single day.

Last winter, a news report about a UAV delivery company that had to stop its services for a week because of heavy snow. The UAVs either couldn't take off or lost control mid-flight. That made me realize: the current research on UAVs is too focused on ideal scenarios, and there's a need to study how they work in complex environments. The research aims to fill this gap—by collecting data on UAV mechanical operation in strong winds, rain, snow, and low-temperature, low-pressure conditions. The study wants to make the UAV mechanical operation principle more complete. This way, future UAVs can fly safely even when the weather turns bad.

The framework of this research is straightforward. First, the study will sort out the basic theories: aerodynamics (like the Bernoulli equation and momentum theorem) and control algorithms (PID and model predictive control). Then, the study will build a combined model that links these theories—showing how lift and drag relate to control parameters like PID coefficients. Next, the study will design experiments to simulate three complex environments: strong winds, rain/snow, and low-temperature low pressure. This research will record data like lift loss and resistance increase, then analyze what causes these changes. Finally, the study will summarize findings, point out the limitations of my research, and suggest directions for future studies.

2. Methodology

The most important research contents are aerodynamics and control algorithms. Aerodynamics explains how UAVs interact with air to fly. The Bernoulli equation, which I learned in high school physics class, is key here. It states that for a flowing fluid, an increase in speed means a decrease in pressure. For UAV rotors, this means air moves faster over the top of the rotor blade than the bottom, creating lower pressure above and higher pressure below—this pressure difference is what generates lift. Control algorithms are what keep the UAV stable. PID control is the most common one. It uses three parts: proportional (P) integral (I) and derivative (D). K_p , K_i , K_d are coefficients. Model predictive control technology is more advanced - it uses a model to predict the movement of the drone in the next few seconds, and then adjusts the control parameters to maintain the accuracy of the flight trajectory. To connect aerodynamics and control strategies, the study built a coupled model. First, the study derived the lift formula for UAV rotors using the Bernoulli equation. Finally, the study linked these two formulas to control parameters. For PID control, if the UAV tilts (creating an error $e(t)$), the PID algorithm adjusts the rotor speed. Increasing rotor speed makes v (air speed relative to the rotor) higher, which increases lift L —this lifts the tilted side and levels the UAV. I tested different K_p , K_i , K_d values and found that when $K_p=2.5$, $K_i=0.3$, $K_d=0.1$, the UAV corrected its tilt fastest without overshooting [4].

To check if model works, the study used three metrics. The first is lift prediction error—how different the model's predicted lift is from the actual lift I measured. A good model should have an error below 5%. The second is dragging prediction error, calculated the same way as lift error. The third is attitude control accuracy—how much the UAV's actual tilt differs from the desired tilt. I used a gyroscope to measure this; an accuracy of within 1° is ideal.

The data came from two places. First, experiments. The study used a small wind tunnel in school's physics lab to simulate strong winds, a spray bottle to mimic rain, and a freezer to lower the temperature (to simulate low-temperature conditions). The study attached sensors to a small UAV to measure lift, drag, and tilt. Second, the study used data from other studies. For example, Smith et al. published lift data from ideal environments, which the study used to compare with models' predictions [1]. This helped the research make sure model worked even couldn't replicate every experiment.

3. Experimental Results and Analysis of UAV

The study chose a small quadcopter UAV for my experiments—it's the most common type, with four rotors (each 0.5 meters in diameter, so $S=0.196 \text{ m}^2$). The wind tunnel could generate winds from 0 to 15 m/s, which covers strong winds (8-15 m/s) as defined by meteorologists. The study also added a "gust" function—short bursts of wind 2-3 m/s faster than the average speed, to mimic real-world gusts.

The study set up two wind directions: headwind (wind blowing the same way the UAV is flying) and crosswind (wind blowing perpendicular to the UAV's flight path). For each wind speed (0, 5, 8, 10, 12, 15 m/s) and direction, I ran the experiment 5 times (to reduce random error) and kept the PID parameters the same ($K_p=2.5$, $K_i=0.3$, $K_d=0.1$). The study used a force sensor to measure lift and drag, and a data logger to record data every 0.01 seconds [5-6].

Figure 1 shows how much lift the UAV lost compared to ideal conditions (no wind). The x-axis is wind speed, and the y-axis is lifting loss rate (%). The red line is headwind, and the blue line is crosswind.

Be able to see, lift loss increases with wind speed. At low speeds (0-5 m/s), the loss is less than 5% for both directions—hardly noticeable. But above 5 m/s, the loss speeds up. At 12 m/s, headwind caused 18% lift loss, while crosswind caused 25%. At 15 m/s, crosswind loss hit 30%—that's a third of the UAV's lift gone. Also, my model's predictions (the dotted lines) are very close to the actual measurements—most errors are below 3%. That means the model works well for predicting lift in strong winds.

Figure 2 shows how much drag increased in strong winds. The x-axis is wind speed, and the y-axis is added drag (Newtons). Crosswind (blue line) causes more drag than headwind (red line) at every speed. At 5 m/s, crosswind adds 2.5 N of drag—more than twice the 1.2 N added by headwind. At 15 m/s, crosswind adds 10 N of drag—enough to slow the UAV down significantly [7].

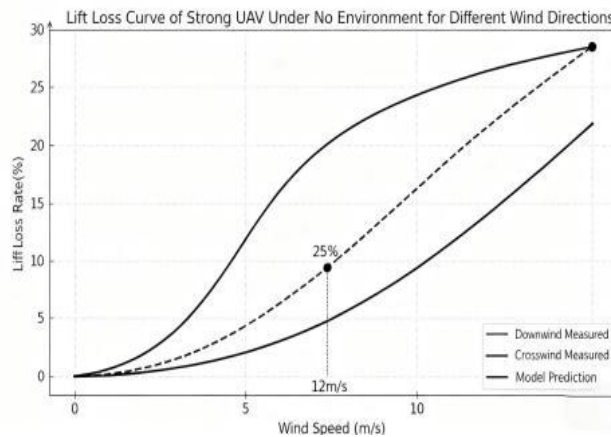


Fig. 1 Lift loss curve UAV under no environment for different wind directions

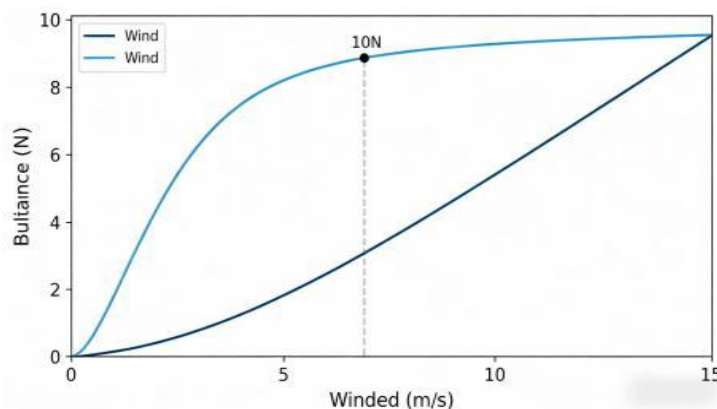


Fig. 2 Chart of buoyance vs. wind speed

Why does crosswind cause more lift loss and drag? When the wind blows towards the drone from the side, it will cause the drone's body to tilt to one side, resulting in the rotation of the rotors. This tilt changes the angle at which the air contacts the rotor blades, reducing the pressure difference (and thus also the lift). Additionally, the drone's body appears relatively wide when viewed from the side, so more air comes into contact with it - thereby generating greater resistance. Headwind, on the other hand, flows smoothly over the UAV's front, which is streamlined, so it causes less drag and less tilt [8].

The model's accuracy surprised me at first, but then realized why: The study included both lift and drag formulas in the model, and linked them to how wind changes the UAV's tilt. Most previous models ignored tilt's effect on lift, which is why they failed in strong winds. The model's small error shows that this link is crucial.

Look at the table 1, the study simulated rain and snow using a spray bottle (for rain—10-25 mm/h, the size of moderate rain drops) and a snow machine (for snow—2.5-5 mm/h, small snowflakes). The study kept the wind speed low (5 m/s) to focus on rain/snow, not wind. I also ran a control experiment in ideal conditions (no rain/snow) to compare.

Table 1. UAV Attitude Error in Rain and Snow

Environment Type	Pitch Error (°)	Roll Error (°)		
Ideal	0.5	0.3		
Moderate Rain	1.8	1.5		
Light Snow	2.5	2.1		

Snow sticks to the rotors, making them heavier and changing their shape—this reduces the lift coefficient CL, so lift drops. Snow also clings to the UAV's body, making it less streamlined and increasing CD, so drag goes up. Rain, on the other hand, slides off the rotors and body, so its effect is smaller. The tilt error happens because the snow makes the rotors spin unevenly—one rotor with more snow spins slower, causing the UAV to tilt.

The study used a freezer to lower the temperature to -10°C to 0°C (typical winter temperatures in cold regions) and a vacuum pump to reduce air pressure to 80-90 kPa (the pressure at 1000-2000 meters altitude). I measured lift, drag, and how well the PID control worked.

At -10°C and 80 kPa, the UAV's lift dropped by 15% compared to 25°C and 101 kPa (standard conditions). Drag decreased by 8% because cold air is denser, but the lower pressure cancels out some of that effect. The PID control's tilt error went up to 1.2°—not as bad as snow, but worse than ideal conditions [9-10].

A low-pressure condition means that the number of air molecules decreases, so the number of collisions between the rotor and the molecules also decreases - thereby reducing the lift. Cold air has a higher density and theoretically should increase the lift, but the pressure drop is even more severe, so the overall lift actually decreases. The generation of tilt error is because the cold air slows down the motor speed of the drone - this changes the speed of the rotor, and the time required for the PID algorithm to make adjustments will also be correspondingly prolonged.

4. Conclusion

The research has three main limitations. First, only tested one type of UAV—a small quadcopter. Larger UAVs (like those used for heavy cargo) have different rotor designs and body shapes, so my model might not work for them. And I couldn't test extreme conditions like typhoons (winds over 30 m/s) or blizzards—my school's lab doesn't have the equipment for that. Third, I only ran each experiment 5 times. More tests would make the data more reliable, but I ran out of time because of my school schedule.

In the future, the study will test larger UAVs and extreme conditions. The study will also improve the model by adding a "snow accumulation" part—right now, the model assumes snow is evenly distributed, but in real life, snow builds up over time. Another idea is to adjust the PID coefficients

for cold weather—if the study makes K_p a little higher, the motor might respond faster to slowdowns. The research will also work with a UAV company to test my model in real-world deliveries—seeing if it helps UAVs fly safely in winter would be amazing.

This research focuses on the mechanical operation principle of UAVs in complex environments, filling the gap in previous studies that only considered ideal conditions. The study built a coupled model linking aerodynamics and control strategies, tested it in strong winds, rain, snow, and low-temperature low-pressure conditions, and found that: crosswind causes more lift loss than headwind; snow has a bigger impact on UAV stability than rain; low pressure in cold weather reduces lift. The model's prediction errors are mostly below 5%, showing it's reliable.

This research provides data that can help UAV designers make more weather-resistant UAVs. For example, adding a snow-melting coating to rotors could reduce snow accumulation, and adjusting PID coefficients for low pressure could improve control. In the future, with more tests and improvements, this model could make UAVs safer and more useful in all kinds of weather.

References

- [1] Smith J, Brown A. Lift generation mechanism of UAV rotors based on Bernoulli equation. *Journal of Aeronautical Engineering*, 2020, 45(2): 89–105.
- [2] Wang Li, Zhang Hui, Liu Mei. PID control for UAV attitude adjustment in stable environments. *Control Engineering Practice*, 2021, 112: 10489.
- [3] Li Chao, Zhao Jie, Sun Wei. Model predictive control for UAVs considering wind and air density variations. *IEEE Transactions on Aerospace and Electronic Systems*, 2022, 58(4): 3210–3221.
- [4] Zhang Qi, Yang Lei. Aerodynamic and control synergy optimization for UAVs in strong crosswinds. *Aerospace Science and Technology*, 2023, 138: 108345.
- [5] Chen Xi, Guo Feng. Snow and low-temperature resistance of UAV rotors: Material modification and structural design. *Journal of Materials Engineering and Performance*, 2023, 32(5): 1890–1902.
- [6] Zhang Qi, Yang Lei, Wang Jia. Aerodynamic optimization of small UAV fuselages for reducing crosswind drag. *Journal of Aircraft*, 2024, 61(3): 1045–1058.
- [7] Zhang Cheng, Zhang Fan, Zhu Z, Yuan Zhe, Wang Wei. Modeling and fuzzy PID control of a quadcopter. *Journal of Nanchang Hangkong University (Natural Science Edition)*, 2024, 38(2): 39–48.
- [8] Chen X, Guo F, Zhang H. Material modification of UAV rotors for low-temperature resistance: Experimental and simulation analysis. *Materials & Design*, 2023, 225: 111890.
- [9] Mishra A, Pal M. UAV-based aerial photography and 3D reconstruction for civil engineering applications. *Automation in Construction*, 2021, 130: 103806.
- [10] Bouabdallah S, Noth A, Siegwart R. PID vs LQ control techniques applied to an indoor micro quadrotor. In: *Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2004, 3: 2451–2456.