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Launching Safety of Small Folding-Wing UAV Against Wind Disturbance

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Abstract. During the launching phase of a small folding-wing UAV(SFUAV), the wings undergo drastic changes in aerodynamic and mass characteristics, the rudder efficiency is low and the anti-disturbance ability is poor, making it highly susceptible to environmental wind disturbances. This study focuses on the motion characteristics of SFUAV in the launching process and the launching safety in wind disturbance environments. Firstly, the wings unfolding dynamic model is established. Secondly, the impact of different wing-unfolding time on launching safety is investigated in calm environment. Furthermore, the effect of different wind speeds and directions on launch safety is analyzed. Finally, to enhance the launching safety of SFUAV against crosswind disturbances, a PID controller is designed to increase the flight stability and safety of the launching process.

Keywords: Small Folding-wing UAV · Launching safety · Wind disturbance

1 Introduction

In recent years, SFUAVs have become the preferred choice for ground-launch by individual soldiers and air-launch by medium to large unmanned aerial platforms, such as the US Army's Switchblade UAV, Raytheon Coyote UAV, and ALTIUS UAV. However, airflow interference seriously threatens the launch safety of small unmanned aerial vehicles [1, 2]. The US military conducted the air launch tests of SFUAV "ALTIUS-600" from the Black Hawk helicopter [3]. The downwash airflow of the helicopter rotor poses a serious threat to the launching of ALTIUS-600. Researchers have argued that "When to deploy the wings, when to start the propulsion system on that air launch effect vehicle, that's the tricky part". During the launching process of SFUAV, the wings fold completely under the fuselage to fully unfold, leading to drastic changes in aerodynamic characteristics. Structural and aerodynamic disturbances pose threat to launching safety, and wind disturbances in the battlefield environment can easily cause attitude instability. Although the takeoff phase of the aircraft only accounts for less than 3% of the entire flight duration, flight accidents occur frequently [4]. Currently, scholars have not conducted sufficient research on the launching safety of folding wing aircraft against wind disturbances. Ye et al. [5] summarized the current launch technologies of UAV and analyzed the advantages and disadvantages of each launch technology. When studying rocket assisted launching of high subsonic UAV under gust disturbances, He et al. found

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that when encountered a lateral wind speed of 5 m/s, the roll angle of UAV reaches up to 68.3°, causing it to lose control and fall to the ground [6].

This article focuses on the motion characteristics and the launching safety of SFUAV during its launching process in windy environments. Firstly, establish and analyze the dynamic model for the wing unfolding process of SFUAV, and analyze its characteristics; Secondly, analyze the impact of different unfolding time of the wings on the launching safety; Thirdly, analyze the impact of different wind speeds and directions on launching safety. Finally, to enhance the launch safety of SFUAV under crosswind disturbances, a flight attitude PID controller was designed. The purpose of the study is to explore the external and internal factors affecting the launching safety of SFUAV and providing safety launch design criteria.

2 Modeling and Analysis of the Folding Wings

The SFUAV in the study is designed as tandem wing and two vertical tails, weight about 1.3 kg, a wingspan of 0.9 m, and a body length of 0.6 m. During the launching phase, the front and rear wings rapidly unfold from 0° to 90°, and the vertical tails unfold from 0° to 105°. The wing morphing process of SFUAV can usually be simplified as a multi-rigid-body system, and modeled by Kane method or Newton-Euler method [7, 8]. Analyzing the unfolding process of SFUAV, the following characteristics can be found:

- The left and right wings are unfolded symmetrically, and the mass and size of the left and right wings are mirror symmetry;
- The front and rear wings morph synchronously, and the mass and size of the front and rear wings are similar;
- The plane of wings rotation passes almost through the center of gravity;
- The mass and size of the vertical tails are relatively small.

Table 1. Difference of C.G. position during wing morphing

Wing unfolding angle	0°	30°	60°	90°	Moving forward
position of C.G	0.247 m	0.245 m	0.243 m	0.240 m	7 mm
Relative position of C.G	40.5%	40.2%	39.8%	39.3%	1%

Table 1 shows the changes of C.G. position during the morphing process: the c.g. only undergoes slightly forward shifting, while the displacements in the y and z directions are negligible. Therefore, based on the four characteristics mentioned above, the following assumptions can be made:

- The additional dynamic disturbance caused by wing morphing only occurs in the longitudinal plane, which mainly affects the x-axis force and pitch moment;
- The additional inertial forces and moments caused by wing morphing can be ignored [9];
- The decisive factors in the morphing process are aerodynamic forces and moments.

Based on the above assumptions, the multi-rigid-body Kane model of the SFUAV wing unfolding process can be further simplified as a quasi-multi-rigid-body system: ignoring the additional forces and moments during the morphing process, the dynamic model is the same as the 6-DOF rigid body model, and the moment of inertia and the aerodynamic forces and moments changes with the wing morphing. Figure 1(a) shows the changes in the three-axis moments of inertia and C.G. position with different unfolding angles. The moment of inertia I_{xx} has increased by 7 times, while I_{yy} and I_{zz} have only increased by 1.2 and 1.5 times, respectively.

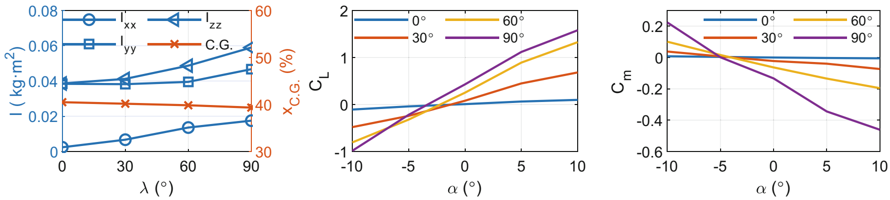


Fig. 1. Mass and aerodynamic characteristics in the morphing process: (a) moments of inertia and C.G., (b) lift coefficient, (c) pitch moment coefficient

The morphing process of wings will induce unsteady aerodynamic effects, which increase with the morphing rate [10, 11]. Due to the short length of SFUAV wings, when the morphing period is >0.2 s, the unsteady aerodynamic effects are weak and can be ignored [12]. Figure 1(b) and (c) show the steady aerodynamics with unfolding angles of 0°, 30°, 60°, and 90°. As shown in the figures, when the wings are fully folded along with the fuselage, the pitch moment is small and almost neutral stable. As the wings unfold outward, aerodynamic force and moment gradually increase.

3 Morphing Period and Uncontrolled Launch Safety

During the launching and takeoff phase, the SFUAV is usually uncontrolled until the wings fully unfolded [13]. Different wing morphing times will significantly impact on the final state of launching. SFUAV's folding wings are usually driven by spring-gear mechanisms. After reviewing literature and considering the size and power of the driving mechanisms, three different deployment times are set: 0.3 s, 0.5 s, and 0.7 s. According to the Switchblade UAV, set the initial conditions for simulation: the launching angle of 45°, the launching speed of 34 m/s, the initial angle of attack of 0°, the launching height of 0 m, and the toward the north.

3.1 Wing Morphing Time

Figure 2 show the results of SFUAV conducting uncontrolled flight under three different wing morphing times. The results show that within 0.1 s from launching, due to the small wing unfolding angle, the gravity plays a major role, the trajectory sinks, and the angle of attack shows an increasing trend. As the wings unfold, the SFUAV generates a strong head-down moment, causing a rapid decrease in angle of attack and entering the negative angle of attack zone, with a maximum negative angle of attack of −7°, which has negative effect on the handover of the FCS. From figure (c), the shorter the morphing time is, the greater the pitch angular velocity is, and the easier it is to lose control. From figure (d), the longer the morphing time, the more the airspeed attenuation. Shorter morphing time ensures higher airspeed in the final state, which conducive to the safe handover of the FCS. However, faster morphing speed places higher demands on the design of spring-gear driving mechanisms. Therefore, the unfolding time of 0.5 s is a compromised choice.

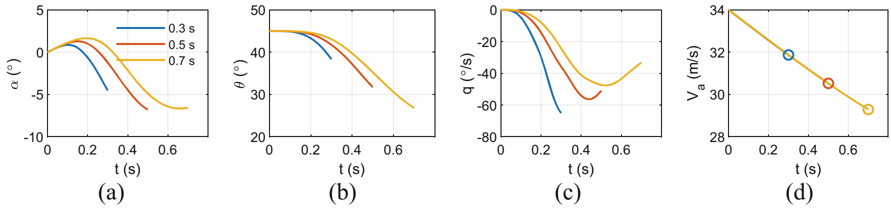


Fig. 2. Launching with different wing morphing times: (a) angle of attack, (b) pitch angle, (c) pitch angular velocity, (d) airspeed.

Considering the structural limit of SFUAV in folding status, the elevator surface can swing within about ±5°. When the SFUAV is preparing for launch, an elevator deflection angle is preset to reduce the excessive head-down moment during launching. The simulation results show that when the elevator is locked at −2°, the elevator can effectively counteract the head-down torque, greatly upgrading the angle of attack and pitch angular velocity and creating favorable conditions for the handover of FCS, as shown in Fig. 3. The preset elevator deflection broadens the selection of wing morphing period and reduces the requirements of the driving mechanisms.

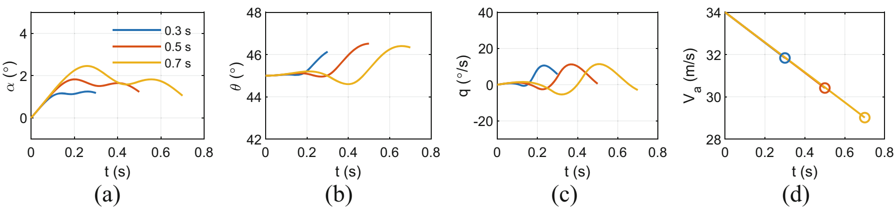
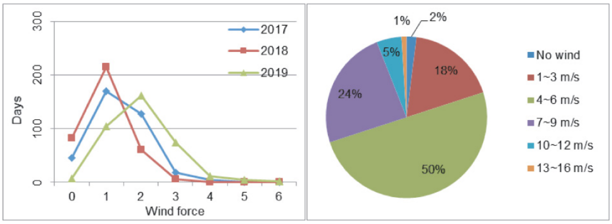


Fig. 3. Launching results of the preset −2° elevator deflection: (a) angle of attack, (b) pitch angle, (c) pitch angular velocity, (d) airspeed.

3.2 Launch Safety Against Wind Disturbance and Unfolding of Vertical Tails

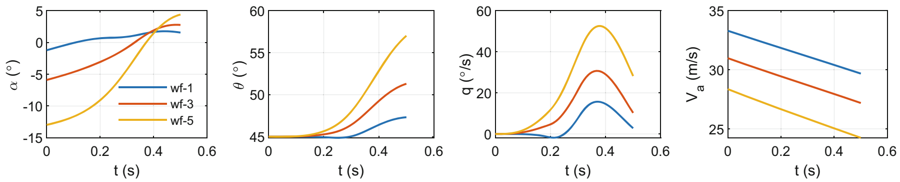
Wind disturbance severely endangers the launching safety of SFUAV. Figure 4 show the wind speed statistics of two regions. For most of the year, the wind speed in City A is less than 5 m/s, and in inclement weather, the wind speed can reach 6–10 m/s. The wind speed with the highest probability in City B in 5 years is 4–9 m/s, with a frequency of up to 74%. To study the launching safety under wind disturbances, three wind speeds of 1m/s, 4.5 m/s, and 9 m/s were selected to simulate the wind force-1, wind force-3, and wind force-5 wind disturbances.



(a) (b)

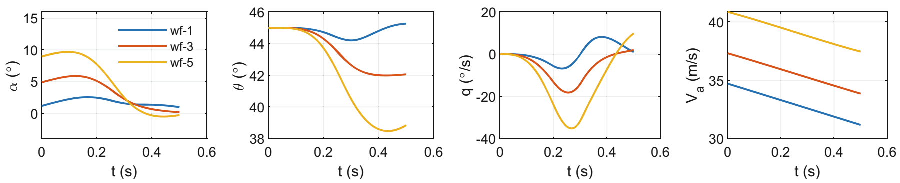
Fig. 4. Wind conditions in two cities: (a) wind force statistical results in three years at northwestern City A, (b) wind speed distribution of five years (2013–2017) at southeastern City B.

Launching Safety in Upwind and Downwind Environments



(a) (b) (c) (d)

Fig. 5. Launching flight status against downwind disturbances: (a) angle of attack, (b) pitch angle, (c) pitch angular velocity, (d) airspeed



(a) (b) (c) (d)

Fig. 6. Launching flight status against upwind disturbances: (a) angle of attack, (b) pitch angle, (c) pitch angular velocity, (d) airspeed

Firstly, the launching safety against upwind and downwind is discussed. The elevator is preset at $-2°$. Figure 5 show the launching of SFUAV in downwind environments.

From figure (a), the higher the wind speed is, the greater the negative angle of attack. In wf-5(wind force-5) wind condition, the initial angle of attack is about −15°. However, when the wings are unfolded, the angle of attack enters the positive region: 2 –5°. From figure (d), the downwind launching leads to a decrease in airspeed, which endangering launching safety. The higher the downwind speed is, the more severe the airspeed decreases. When launched against the wind, it will have the opposite effect, as shown in Fig. 6. The angle of attack during launching is positive, and the final angle of attack is around 0°. The upwind launching has a significant lifting effect on airspeed. The higher the airspeed, the safer the drone. Therefore, upwind launching is superior to downwind launching.

Launching Safety in Crosswind Environments

The Timing of Unfolding the Vertical Tails. Due to the light weight of the SFUAV's vertical tails, the additional inertia disturbance torque generated by the vertical tails morphing can be ignored. At the same time, the vertical tails only generate aerodynamic torque in crosswind environments. Therefore, the timing of the vertical tails morphing is studied with crosswind disturbances. When the vertical tail is fully unfolded compared to fully folded, the roll and yaw moments caused by the sideslip angle increase by about 5 times and 12 times, respectively. In uncontrolled situations, the yaw and rolling moments generated by the vertical tail are unfavorable factors for launching safety and can seriously affect the final state. According to the morphing of the wings, three cases for the unfolding timing of the vertical tails are considered: leading, synchronous and lagging, that is, the vertical tails unfold faster than the wings, the vertical tails unfold synchronously with the wings, and the vertical tails unfold more slowly than the wings.

Figure 7 show the SFUAV launching results at three vertical tail unfolding timings in the condition of wind force-3 crosswind and −2° preset elevator deflection. From figure (c), the leading morphing of the vertical tails against crosswind disturbance result in a roll angle of about 40°, which has a significant impact on the angle of attack and sideslip angle, posing a serious threat to the launching safety. The effect of synchronous morphing and lagging morphing is relatively small, and the fluctuation amplitude of the attack angle is less. The roll angle in the final state is less than 20°.

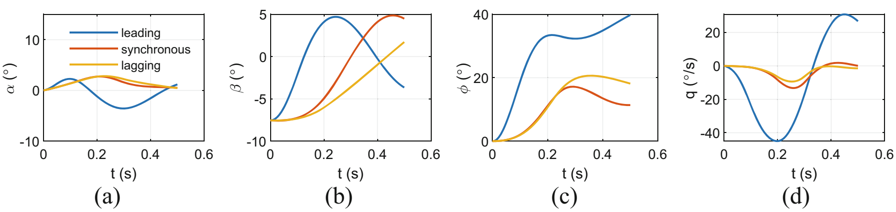


Fig. 7. Launching in wind force-3 Crosswind environment with different vertical tails morphing Timings: (a) angle of attack, (b) sideslip angle, (c) roll angle, (d) pitch angular velocity

Table 2 shows the final roll angle of SFUAV under different lateral wind forces and vertical tails morphing timings. The leading morphing of the vertical tails results in a significant roll angle at the final of launching. And the higher the wind speed, the greater the roll angle, which seriously diminishes the safety of the launching. In wind force-5 environment, if the vertical tails morphing faster than the wings, the SFUAV may suffer a roll angle of up to 81°, inevitably leading to crash. Considering the three morphing timings, synchronous morphing is a recommendable choice. When designing the vertical tails unfolding driving mechanism, it is necessary to ensure the synchronous morphing of the vertical tails and the wings as much as possible.

Table 2. Roll angle against different crosswind disturbances

Lateral wind force	Vertical tails unfolding Timing		
	Leading	Synchronous	Lagging
1	8.5°	2.1°	3.8°
3	38.6°	11.6°	18.3°
5	80.9°	40.1°	47.3°

Launching with Crosswind Disturbance in Synchronous Morphing According to the previous results, the vertical tails unfolding timing is set to be synchronized with the wings, the morphing period of 0.5s, and the elevator deflection preset of −2°.

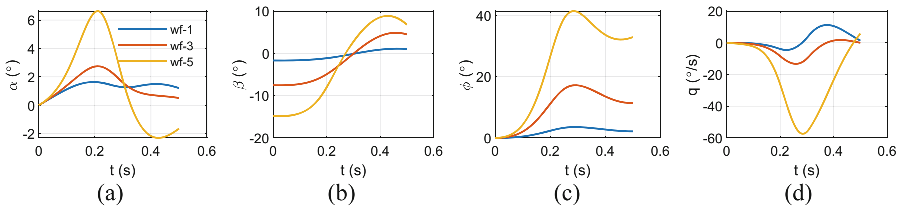


Fig. 8. Launching against crosswind disturbance in synchronous morphing timing: (a) angle of attack, (b) sideslip angle, (c) roll angle, (d) pitch angular velocity

Figure 8 reveal the launching results of SFUAV in different lateral wind forces. During the launching in windy day (≤force-5 wind), the angle of attack varies within the range of −3 –8°, and the terminal angle of attack is within ± 2°. The initial value of the sideslip angle increases with the lateral wind force, and the final state is within 0–7°. Under force-5 crosswind disturbance, the instantaneous roll angle reaches up to 41°, posing a serious threat to launching safety. In summary, due to the unique structure of SFUAV, the launching safety is jointly affected by its own structural and external disturbances. From the perspective of structural design, it is advisable to design a morphing period of 0.5 s, and the vertical tail is well synchronized with the wings. From the perspective of resisting wind disturbances, upwind launching should be priority, followed by downwind launching, and finally crosswind launching.

4 Launching Safety with PID Controller

The battlefield is changing rapidly. Limited by the launching environment, it is often difficult for the operators to choose the best launch window, which also puts forward higher requirements for the robustness of the launching system. Introducing active control during the launch phase is an effective solution to further improve the safety of the launching phase.

Due to the compact structure of SFUAV, the deflection of the aerodynamic control surfaces is limited with unfolding angle. As shown in Table 3, the control limit can be divided into two phases: Phase I, when the wing unfolding less than 30°, the control limit at this time is ± 5°; in Phase II, the control surface limit is ±25°.

Table 3. Limit of control surfaces during morphing

Control surface type	Elevator, Aileron		Rudder	
	Phase I	Phase II	Phase I	Phase II
Unfolding angle, °	0–30	30–90	0–30	30–105
Control limit, °	5	25	5	25

To ensure the launching safety of the SFUAV, BTT control method is adopted to prioritize ensuring the angle of attack, sideslip angle, and roll angle within a reasonable range, to obtain sufficient ground clearance. Therefore, a three channel PID controller is designed to ensure the stability of the angle of attack, sideslip angle and roll angle. The preset deflection of elevator is $-2°$. Flight control command is: $\alpha_c = 1°$, $\phi_c = 0°$, $\beta_c = 0°$。

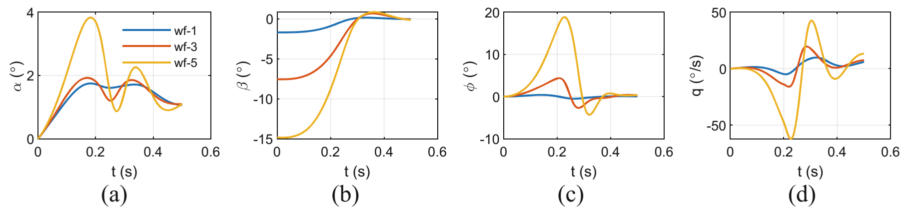


Fig. 9. PID control under different crosswind disturbances: (a) angle of attack, (b) sideslip angle, (c) roll angle, (d) pitch angular velocity

The launching results after introducing an attitude PID controller is illustrated in Fig. 9. Comparing with Fig. 8, the angle of attack and sideslip angle are quickly stabilized via attitude PID controller, and the excessive roll angle caused by crosswind disturbance was significantly mitigated. At the final of the launching process, the flight attitude angle can basically track the command. Under force-5 crosswind disturbance, the SFUAV has an instantaneous roll angle of about 19°, and the angle of attack and sideslip quickly stabilize, ensuring the launching safety.

5 Conclusion

This article discusses the launching safety issue of SFUAV under wind disturbance. Considering the attenuation of airspeed and the power of the drive mechanism, the wing morphing time is set to 0.5 s. Considering the influence of crosswind disturbances, it is advisable to design the vertical tails unfolding drive mechanism to ensure synchronous morphing with the wings. When launching SFUAV uncontrolled, preset elevator −2°. The control torque generated by elevator can greatly improve the angle of attack and pitch angular velocity at the end of launch. In wind disturbance environments, it is advisable to adopt upwind launching, followed by downwind launching, and avoid crosswind emission. The greater the lateral wind force, the greater the harm to launch safety. Finally, a three channel PID attitude controller is designed to further enhance the safety of SFUAV launching in crosswind environments. The problem of excessive roll angle caused by crosswind disturbance can be significantly improved, providing better handover conditions for switching to the cruise control mode.

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