VERTICAL LANDING OF A FIXED-WING UAV USING THE FLAT SPIN

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Abstract

This paper studies a feasibility of a novel landing method especially in a limited space for an ordinary Unmanned Aerial Vehicle (UAV) using the flat spin. Use of the combination of an all-flying tail with large deflection angle has been found effective for quick intentional flat spin entry, and the higher propeller rotational speed as well as the high all-flying tail deflection angle has been also found effective for flatter or even positive pitch attitude during the spin. One of the key issues to realize flat-spin landing is to control its descent path toward the desired landing point. The influences of change in pitch attitude on the descent path are examined in flight tests, and the periodic pitch attitude change caused by the deflection of the all-flying tail with full throttle was found effective for the descent path control.

1 Introduction

It is often difficult to find out a flat large area for conventional take-off and landing for a fixed-wing UAV in practical missions. We could use a catapult for take-off, however, there is no handy and satisfactory method for landing especially in a limited space.

The flat spin of a fixed-wing airplane is generally considered as an uncontrollable and undesired maneuver to be avoided by all means, and many studies have been done focusing on the prevention or the recovery from the flat spin [1-3]. However, the descent speed during the flat spin is fairly low, and the attitude of the airplane is literally almost flat. If we can positively control the descent speed and the airplane's attitude at the moment of touchdown to a tolerable level, and also if we can control the descent path toward the desired touchdown point like the autorotation of a helicopter, the flat-spin landing can become a handy and convenient landing method especially in a limited space for small UAVs.

In order to realize the flat-spin landing, the following issues have to be solved,

1. Method for intentional flat spin entry independent of C.G. position.
2. Descent speed control which is slow enough for touchdown.
3. Attitude control which is flat enough for touchdown.
4. Descent path control toward the desired touchdown point.

Regarding the issues No.1 to No.3 above, the combination of a large deflection angle of the all-flying tail and higher propeller rotational speed for the generation of more pitching moment has been found effective by the Authors [4], and their effects are summarized briefly later. In order to control the descent path, i.e. to solve the issue No.4, some controllable centripetal force is required for changing the descent path arbitrarily. The Authors consider to make use of the thrust produced by the propeller for proceeding to desired direction by applying it periodically during the flat spin. In this paper, Controllability of the descent path during the flat spin using the pitch attitude change is examined by flight tests, and the periodic control of the pitch attitude is shown to be effective by using the periodic deflection of an all-flying tail with full throttle.

2 Flight Testing

2.1 Test Vehicle

The test vehicle we have chosen is a motor glider UAV named "Phoenix" which has been originally designed and developed for aerosol observation and sample return from the upper atmosphere [5]. It has an ordinary configuration for a motor glider, with tricycle gear, T-tail, and foldable propeller. It is not designed considering the easier aerobatic maneuverability including flat spin. The appearance and its specifications are shown in Fig.1 and Table.1 respectively.

Fig.1 Test Vehicle "Phoenix"

Table 1. Specifications of "Phoenix"

Parameter	Value
Wing span(m)	2.77
Wing area (m^2)	0.57
Wing aspect ratio	12.7
Horizontal tail span(m)	0.508
Horizontal tail area (m^2)	0.070
Horizontal tail aspect ratio	3.69
Elevator area to Horizontal tail area ratio	0.257
Maximum elevator deflection angle (deg., trailing edge up)	-25.0
Length(m)	1.50
Weight(kg)	8.0
C.G. (% MAC)	28.0
Stick-fixed neutral point h_n (% MAC)	47.4
Propulsion motor	Hacker A50-12L
Propeller (inch)	14×10

The C.G. position is fixed at 28%MAC which gives 19.4% MAC of static margin in all the following tests which will be described later. Spins are classified as in Table 2 according to the literature [1]. It has been confirmed in a flight test that it is not difficult to make Phoenix enter steep spin with full-up elevator deflection (-25deg) intentionally with 28% MAC C.G., and also confirmed that it is impossible to make its attitude shallower with full-up elevator deflection.

Table 2. Spin Classification [1]

Spin mode	Pitch angle θ (deg)
Steep	-70 ~ -60
Moderately steep	-60 ~ -45
Moderately flat	-45 ~ -25
Flat	-25 ~ 0

Phoenix is equipped with an emergency parachute developed by the authors. It is different from so-called spin shute. It is installed inside the canopy with a pilot chute ejected vertically by a spring, and the UAV can land on the ground with flat attitude.

2.2 Instrumentation

Schematic of the flight control and data collection system is shown in Fig.2.

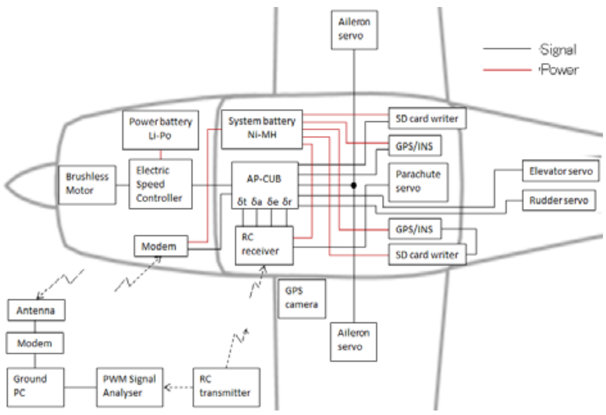

Fig.2 Schematic of Flight Control and Data Collection System

Measurement of the major parameters such as attitude angles, angular rates, accelerations, and pressure altitude associated with the flat spin is done by a GPS/INS (LORD Microstrain 3DM-GX5-45). Vertical speed is calculated from pressure altitude by differentiation, and corrected for non-standard pressure and temperature assuming the vertical component of wind is zero. A flight control system named "AP-CUB" [6] is also installed. AP-CUB has been originally developed for automatic flight for various missions [4, 7], and it is used for the automatic control of surface deflections and throttle position during the flat spin in this study. The data are sampled at every 20msec and stored in a micro SD card.

2.3 Procedure of Flight Testing

Flight tests are carried out using a grass runway with conventional take-off and landing. After the take-off by manual control, the pilot (the Authors) raise the altitude to approximately 300 to 400m from the ground also by manual control, then slows down and initiates the spin entry procedure; i.e. throttle idle, gradual full aft stick and full left rudder. The UAV enters in the flat spin easily with large deflection angle of the all-flying tail which will be described later, and preplanned control surface deflections and throttle position are given by the flight control computer (AP-CUB) by switching from manual control to automatic control in order to give the precise surface deflections and throttle position as intended. After approximately 10 seconds of the flat spin, the pilot make the UAV recover from the flat spin by setting the control surface deflections to the original position by manual control. Full opposite rudder is not required for the recovery. The pilot pulls up after recovery and climb up to the altitude for next test. This process continues two to three times depending on the battery capacity for the motor. Conventional landing on the runway is carried out by manual control. Total flight time is approximately 5 to 6 minutes.

3 Effect of Deflection Angle of the All-Flying Tail and Propeller Rotational Speed on Pitch Attitude in Flat Spin

An all-flying tail with large movable angle (-90deg) is employed by replacing a conventional stabilizer-elevator tail in order to generate more pitch-up moment at higher angle of attack during the spin. The appearance of the original conventional tail and the all-flying tail are shown in Fig.3 and Fig.4 respectively.

(a)δ_e=0(deg) (b) δ_e= -25(deg)

Fig.3 Original Tail

(a)δ_e=0(deg) (b) δ_e= -90(deg)

Fig.4 All-flying Tail

The Authors have already found that the combination of large deflection angle of the all-flying tail around -90deg and full throttle make UAV's pitch attitude almost flat or even positive [4]. Here the effect of them on pitch attitude is summarized in order to make use of the results later for the control of descent path.

In order to investigate the effect of the deflection angle of the all-flying tail on the pitch attitude during the flat spin, 24 flat spins with one deflection angle at one time, and changing it from -39 (deg) to -100 (deg) are carried out. They include flight data with two moment of inertia because some payloads including onboard camera have replaced and led to some gain in weight and moment of inertia. They are distinguished as "high" and "low" moment of inertia in relative sense in the figures later. Test condition for the series of flight tests are shown in Table 3. Later, the rotational speed is found that it also largely affects the pitch angle during the flat spin, but throttle position is set to 100% corresponding to approximately 8700 (rpm) in this series of flight tests. Rotational direction of the propeller is clockwise looking from behind.

The effect of the rotational speed of the propeller will be shown in next section.

Table 3. Test Conditions for the investigation of Deflection Angle vs Pitch Attitude

Control Surface	Value
All-flyin Tail (deg)	-39 ~ -100
Ailerons (deg)	0
Rudder (deg)	18 (Full Left)
Throttle (%)	100

The relationship between the deflection angle of the all-flying tail and the averaged value of the pitch angle during one flat spin is shown in Fig.5. The data with relatively "high" moment inertia are indicated in orange squares, and "low" are in blue circles. Standard deviations of the pitch angle during the spin are also indicated by error bars.

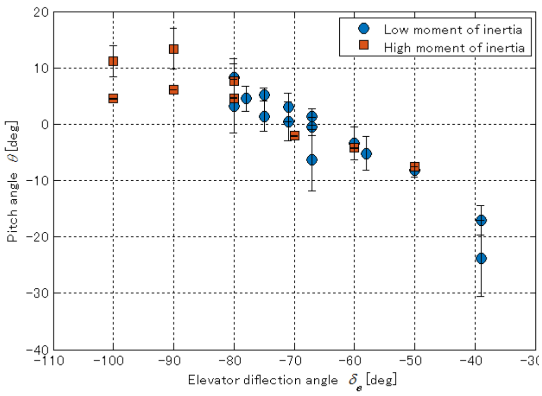

Fig.5 Relationship between Deflection Angle of the All-flying Tail and Pitch Angle with Full Throttle

As seen from Fig.5, pitch angle of the UAV during the flat spin becomes flatter and even positive up to more than 10 degrees as the deflection angle of the all-flying tail becomes negatively larger, i.e. more trailing edge up.

This pitch-up attitude is considered to occur clearly due to the pitch up moment generated by the all-flying tail of which angle of attack becomes appropriate by a large deflection angle together with the slipstream of the propeller. There seems no dependency on the difference in moment of inertia.

Fig.6 shows the pitch angle during the flat spin changing the propeller rotational speed. 8 flat spins with one propeller rotational speed at one time, and changing it from 0 (rpm) to 8600 (rpm) are carried out. The deflection angle of the all-flying tail was set to only -80 (deg). Other test conditions are shown in Table 4. Throttle positions 0, 25, 50, 75, 100% correspond to 0, 3198, 5580, 7477, 8652 (RPM) respectively.

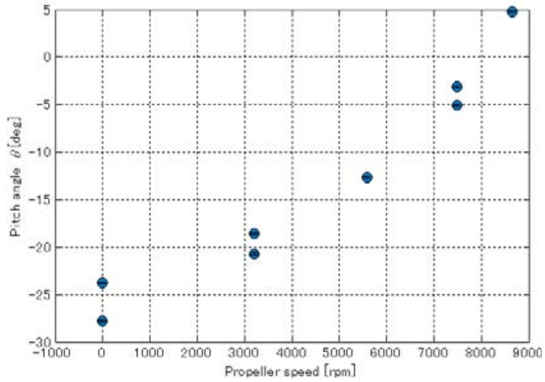

Fig.6 Relationship between Propeller Rotational Speed and Pitch Angle with -80deg deflection

Table 4. Test Conditions for the investigation of Rotational Speed of a Propeller vs Pitch Attitude

Control Surface	Value
All-flyin Tail (deg)	-80
Ailerons (deg)	0
Rudder (deg)	18 (Full Left)
Throttle (%)	0, 25, 50, 75, 100

Fig.6 indicates that the pitch attitude is greatly affected also by the rotational speed of a propeller, and the pitch angle becomes flatter or even positive with the increase in propeller rotational speed. The pitch angle is around -25 (deg) when the RPM is zero in Fi.6, while the pitch angle increases up to around 5 (deg) as shown in Fig.5 with the same -80 (deg) of deflection angle if full throttle is applied. This is evidently due to the effect of the propeller rotation.

This phenomenon is considered not only due to the effect of slipstream of the propeller on angle of attack of the tail, but also due to the effect of so-called Propeller-factor (P-factor) and gyro precession of the propeller rotation. The angle of the resultant flow to the propeller is considered quite large due to the descent speed and the spin rotation. The resultant flow comes in almost underside of the UAV, and this causes pro-spin rotation due to P-factor, i.e. the difference in thrust in advancing blade and retreating blade against the incoming flow. The pro-spin rotational torque induces the pitch up moment due to gyro precession of the propeller. Therefore, the spin direction in this case becomes counter clockwise looking from the top.

4 Method for Descent Path Control

In order to change descent path, some centripetal force is required. We can make use of thrust of the propeller because the thrust is the almost only force perpendicular to the descent path during the flat spin. We have already seen that pitch angle can be controlled by the combination of the deflection angle of the all-flying tail and the rotational speed of the propeller, and we can control the direction of the horizontal motion by controlling the horizontal component of the thrust. There are two ways to control the horizontal component of the thrust either by controlling the rotational speed of the propeller and by deflection angle of the all-flying tail.

4.1 Effect of the Periodic Change in Rotational Speed of the Propeller

Change in rotational speed of the propeller will cause the change in pitch angle as seen in the previous section, then it could lead to the change in horizontal thrust component as a centripetal force. Several flight tests were carried out. However, the results show that this method is not very much effective because it was hard to maintain periodic pitch attitude change by periodically and alternatively changing the throttle position between 0% and 100%. The difficulty is caused by the relatively long time delay of the propeller rotational speed against the command. We could not obtain satisfactory results even increasing 0% throttle position to 50%. In this case, although the maintaining the flat spin was easy, and the change in pitch angle was fairly reduced, and accordingly the change in descent path was not observed as intended.

4.2 Effect of the Periodic Deflection of the All-Flying Tail

We can change pitch attitude easily by deflection angle of the all-flying tail with full throttle in the flat spin as mentioned earlier. We may control the horizontal component of the throttle just by changing the pitch attitude via the deflection angle of the all-flying tail. In this case, the time lag of the throttle does not occur because the throttle position is always full, while the time lag between the pitch angle and the deflection angle of the all-flying tail could be a problem. In the flight tests, we gave the desired direction to proceed as FSDC as shown in Fig.7. The deflection angle of the all-flying tail was set to -90 (deg) during the heading angle is in the area shown as FSDL and FSDR around FSDC in Fig.7, and the deflection angle was alternatively set to -20 (deg) in the rest of the angle. Other conditions are shown in Table 5.

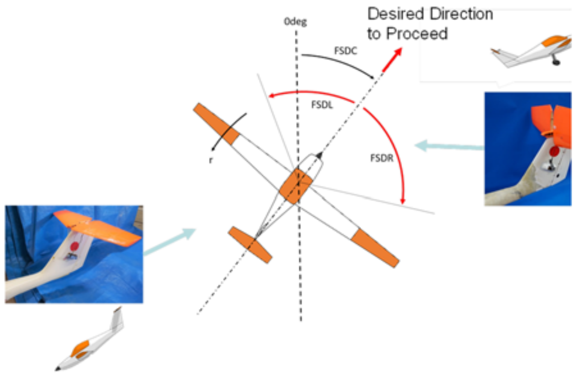

Fig.7 Relationship between the Desired Direction and Commands to the Flight Computer

Table 5. Test Conditions
for the investigation of Direction Control

Control Surface	Value
All-flyin Tail (deg)	-90 or -20
Ailerons (deg)	0
Rudder (deg)	0
Throttle (%)	100

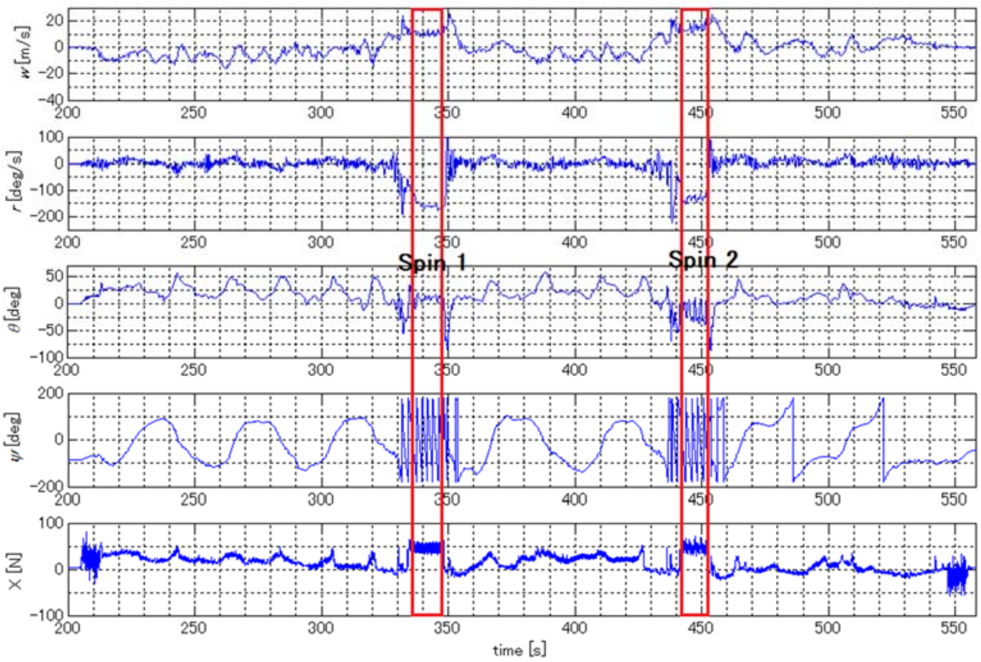

Fig.8 Descent Speed w, Spin Rate r, Pitch Angle θ, Yaw Angle ψ, and External Force in X direction in Spin1 and Spin2 (Surrounded by Red Squares)

Two flat spins were carried out in one flight test. First spin (Spin 1) is done with the constant all-flying tail deflection as -90 (deg) and full throttle. In the second spin (Spin 2), periodic deflection angle control is performed using the flight computer (AP-CUB) with full throttle. Time history of descent speed w(m/s), spin rate r(deg/s), pitch angle θ (deg), yaw angle(deg), and the external force (N) in X direction in body axis calculated from the acceleration are shown in Fig.8. Spin 1 and Spin 2 correspond to the part surrounded by a red square respectively in Fig.8.

It is seen that pitch angle changes largely from around -40 (deg) to 10 (deg) periodically in Spin 2, while it is almost constant approximately 10 (deg) in Spin 1. This difference in pitch angle made a difference in 2D Flight track (GPS track) as shown in Fig.9. It is drawn looking from the top by making both of the start point of the spins coincide. The direction of the flight track of Spin 2 is evidently different from that of Spin 1, but the direction is different from the intended direction (FSDC) by 90 (deg). This is due to the time delay between the deflection angle of the all-flying tail and pitch angle change.

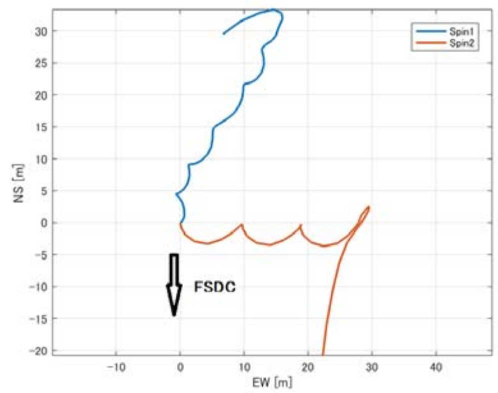

Fig.9 Flight Tracks of Two Spins with and without Deflection Angle Periodic Control

Fig.10 shows the horizontal component of the external force in X direction in body axis in polar axis form. It is seen from Fig.10 that the moving direction of the UAV in Spin 2 in Fig. 9 (East) coincides with the direction where maximum external force appears in Fig.10 (East). This result indicates that the periodic change in pitch angle using the deflection change of the all-flying tail with full throttle generates effective centripetal force to change the descent path to the intended direction.

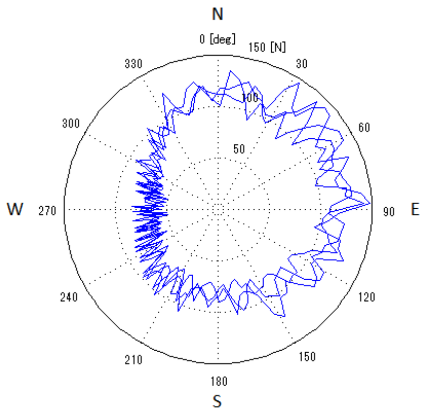

Fig.10 Horizontal Component of External Force in X direction in Body Axis

5 Conclusion

In order to use the flat spin as a means for landing in a limited space, impact speed and attitude at touchdown are important as well as the controllability of the descent path to the desired touchdown point. In this study, the Authors focused on the controllability of the direction of descent path during the flat spin, and the method using the periodically changing thrust of the propeller as the centripetal force to change direction was investigated experimentally. Periodic change in thrust can be realized by pitch angle control during the flat spin, and the method which uses periodic change in deflection angle of the all-flying tail with full throttle is found effective to change pitch angle, external force in desired direction, and thus the moving direction with approximately 90 degrees of phase lag.

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