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Roto-Stabilizer for Superb Pitch-Related Post-Stall Maneuvers and STOL

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Abstract

Stabilizers and their control surfaces are vital components in maneuvering an airplane during flight. However, a shortcoming of stabilizers is that they require airstream or propeller wash for them to work properly. In this work, we propose the concept of roto-stabilizer as viable substitution for conventional horizontal stabilizer. A key benefit of the proposed technique is its ability to exert powerful moment in the absence of forward airspeed or propeller wash. Proof of principle is demonstrated via computer simulations. Results reveal that new aerobatic maneuvers are made possible. Furthermore, when implemented in canard configuration, it is possible to achieve ultra-STOL and VTOL.

Keywords

Roto-Stabilizers, Roto-Canard, Aerobatics, STOL, Tropical Cyclone

1. Introduction

It is often a marvelous sight to behold when a modern airliner takes to the sky on its maiden flight. This is a result of cumulative engineering marvel after more than a century of flight. Stabilizing fins known as stabilizers are key components in maneuvering an aircraft, and much of the effort to develop stabilizers and their control surfaces was done during the 1800s when aviation pioneers such as Sir George Cayley of Britain and Alphonse Penaud of France began experimenting with models as well as manned gliders [1]. The typical airplane today still very much inherits the basic design concepts Cayley developed during the first half of the 19th century. While the fin-based stabilizers perform well even in supersonic domain, the shortcoming becomes apparent close to stall or in post-stall regimes in which aerobatic flights frequently operate. The shortcoming lies in the fact that a horizontal stabilizer and its elevator require sufficient air-flow in order to effectively actuate flight controls. For that reason, most aerobatic fixed-wing aircrafts are de-signed such that the control surfaces are immersed in propeller wash so that they are able to perform many of the signature post-stall aerobatic maneuvers such as prop-hang (vertical hover), flatspin, blender, harrier, tailslide, waterfall and their derivatives [2] [3] [4] [5]. The aerobatic maneuvers most relevant to this work are harrier and waterfall. The harrier maneuver is one in which the aircraft flies in its post-stall regime in trim at high angles of attack near 45˚ with nose-up elevator input [5]. This maneuver relies on lift from the wing and the vertical component of propeller thrust in order to sustain level trimmed flight [5]. A distinctive characteristic of these aircraft is the thrust-to-weight ratio that exceeds unity [2] and therefore can potentially be used to create VTOL airplanes with ultra-agility.

However, the requirement of having sufficient airflow over a stabilizer imposes a fundamental limit on the scope and quality of post-stall maneuvers an aerobatic airplane can perform. Take for example, the "waterfall" maneuver, where an airplane pivots 360˚ over its pitch axis with very little forward motion, and it can involve one or multiple flips [6] [7]. Aerobatic airplanes with conventional horizontal stabilizer will have difficulty executing the "waterfall" maneuver despite its seemingly simple description, because in order to exert pitching moment around the pitch axis, strong propeller wash, and hence forward propulsion must be presence which inevitably pulls the aircraft forwards. It would be highly desirable to overcome such shortcoming, so that propeller thrust and pitch control of the airplane can be operated independently.

In this paper, we thus propose and investigate the concept of "roto-stabilizer" as a possible replacement for traditional stabilizers as a solution to overcome the limitations of conventional stabilizers in the post-stall regimes. The validation study will involve computer simulations. Advantageous of the proposed concept will be discussed, including possible benefits to full scaled airplanes.

2. Materials and Method

2.1. Concept of Roto-Stabilizer

The concept of roto-stabilizer involves the use of one or more impellers as primary substitution for the stabilizer of interest. The concept is generally applicable to both horizontal and vertical stabilizers, but the primary focus in this paper is on the horizontal stabilizer given its distinct advantages. The roto-stabilizer is expected to be applicable to a canard, or anaft mounted stabilizer as shown in **Figure 1**. The axis of rotation of the impellers or rotor is parallel to the vertical axis of the airplane. Assuming for now that the impellers are of variable pitch, then the roto-stabilizer will be able to exert effective pitching moments about the pitch axis of the aircraft even when the airspeed of the aircraft is zero. If validated, this will potentially open up a broad spectrum of possibilities for airplane aerobatics as well as short takeoff and landing (STOL) with wide ranging applications, including severe weather reconnaissance and personal aviation.

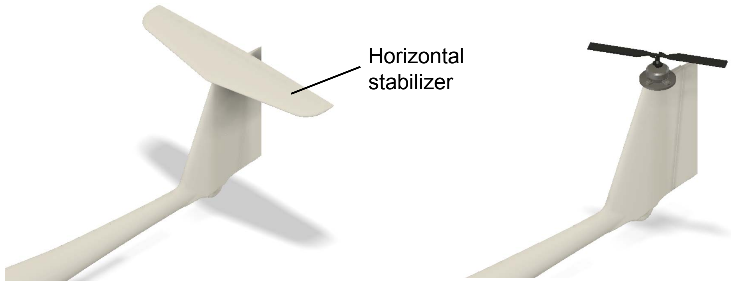

Figure 1. The proposed roto-stabilizer as viable substitution for conventional horizontal stabilizer.

2.2. Simulations

The proof of concept was demonstrated via computer simulations using the RealFlight®[1] 8 simulator [8]. Several different airplane models will be used to explore the viability of the concept. The as-supplied simulation model "Mistral 3M", which is an engineless sailplane as shown in **Figure 2(a)**, was selected as the RC model to explore and demonstrate the basic characteristics of roto-stabilizer. The model in its pristine configuration has a wing span of 3.16 m and a wing loading of 30.35 g·dm^{-2}. **Figure 2(b)** shows the tail section (empennage) of the Mistral 3M including the horizontal stabilizer in yellow outline. The concept of roto-stabilizer was applied to the model by removing the horizontal stabilizer and replaced it by a 2-bladed variable-pitch (V-pitch) propeller of diameter 254 mm, but only the direct-drive motor driving the V-pitch propeller is shown with red outline in **Figure 2(c)**. These changes were carried out using the Aircraft Editor within the simulator. The variable pitch range was set to ±10˚, and the propeller was driven by a brushless motor of 1750 kV (rpm·V^{-1}) as depicted in **Figure 2(c)**. The center of gravity position of the aircraft was kept almost unchanged and 1-axis angular position dependent gyro was added for flight stabilization in the pitch axis. No changes were made to the ailerons and rudder. The sailplane was flown in manually piloted mode during simulations. Note that during simulation runs, the original graphical model of the Mistral 3M was displayed despite changes have been made to its physical properties, such as removal of horizontal stabilizer in this case. The correct graphical model would have to be updated separately but for this simulation work, it was not done because the graphical model has no effect on the flight physics. During the simulation run, the variable-pitch propeller was rotating at a nearly constant rotational speed of 6800 rpm and generating a maximum static thrust of 3.8 N on either direction. The modified Mistral 3M with the roto-stabilizer implemented has a final wing loading of 32.94 g·dm^{-2}. The on-screen real-time simulated flights were recorded and compiled into a video clip using the Camtasia® 9 software [9].

3. Simulation Results and Discussion

To evaluate the flight performance of the engineless Mistral 3M equipped with

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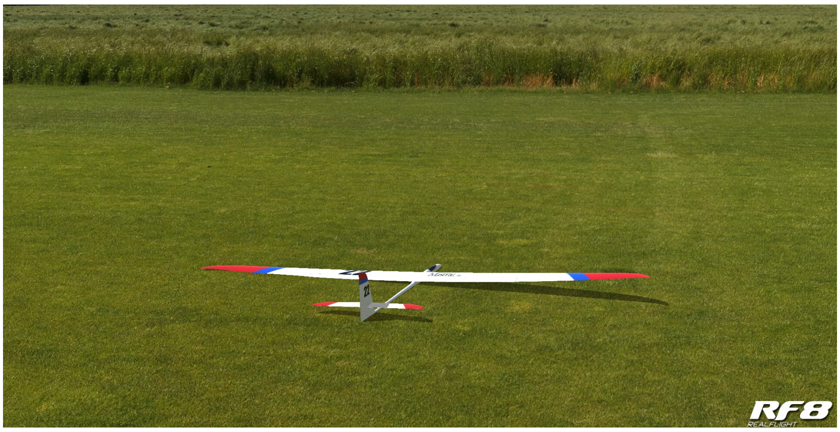
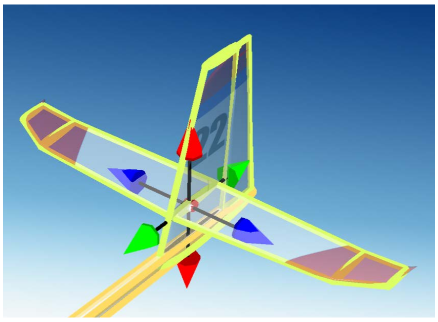


(a)



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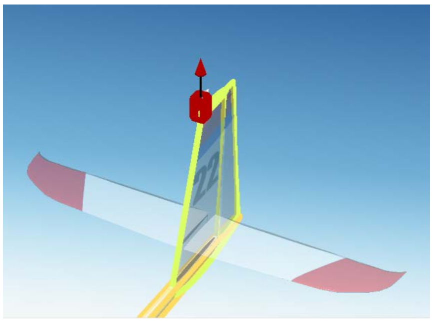


(c)

Figure 2. (a) The as-supplied simulation model "Mistral 3M", (b) The empennage with the horizontal and vertical stabilizers in yellow outline, and (c) The horizontal stabilizer was removed and substituted by the roto-stabilizer with its direct-drive motor highlighted in red.

roto-stabilizer, Sierra Nevada Cliff was selected as the airport for the ability to take advantage of the orography updrafts needed to keep the sailplane airborne. The horizontal wind speed was set to only 12 km·h^{-1} to prevent the airplane from gaining excessive kinetic energy from the environmental wind so as to characterize its performance more accurately, but this also means that the margin of error on the part of the model pilot is small during flight testing and therefore considerable precision flying was required. Level flight simulations revealed that the flying characteristics of the Mistral 3M with roto-stabilizer was hardly distinguishable from those of the original Mistral 3M, and particularly, there was no observable oscillation in the pitch or loss of control. Figure 3 shows a close-up screenshot of the airplane during the "straight-and-level" flight testing with wind of 20 km·h^{-1} and updraft of 1.7 m·s^{-1}. The climb rate of the sailplane as per the variometer was 1.0 m·s^{-1}. The gyro's heading hold and rate gains were set to 100% with other parameters at default values.

The sailplane also performed basic aerobatic maneuvers such as tight turn, loop, half roll, and inverted flight without any noticeable qualitative difference from those of the original airframe. The sailplane was then evaluated for its ability to perform waterfall, which is the maneuver it was specifically designed to

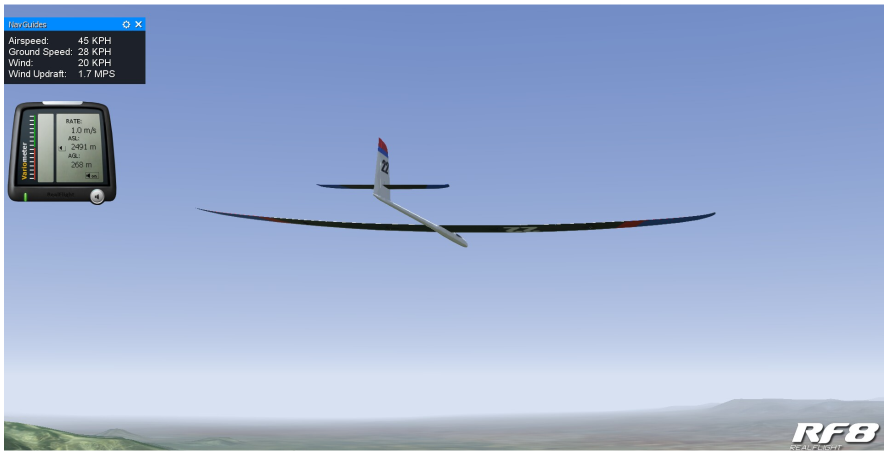


Figure 3. A close-up screenshot of the roto-stabilizer enabled Mistral 3M during the "straight-and-level" flight testing.

perform. The engineless sailplane performed the waterfall maneuvers (single- and multi-flip) with ease and grace—a feat that few, if not any, conventional motorless sailplanes, whether full-scaled or otherwise, could have accomplished. The On-screen simulated flights of the Mistral 3M with roto-stabilizer is available as Video 1 (click on the link to view). The video includes level flight, basic aerobatics mentioned above, and the waterfall maneuvers (single- and multi-flip). To perform the waterfall maneuver, it started from level flight with a 1/4 loop up into a vertical climb. When the sailplane's momentum has decreased sufficiently, "down elevator" was applied which pushed the nose of the sailplane downwards, thus initiating the first flip. The waterfall maneuvers were often concluded with a steep dive to regain airspeed to prevent stalling.

Further characterization on the roto-stabilizer was performed at higher airspeeds to determine the robustness of the technique. The environmental wind speed (hence the resultant orographic updraft) was increased to 80 km·h^{-1} (the maximum value permitted by the simulator) though the intensity increased with altitude. The sailplane would dive at a relatively steep nose angle (approximately, 30˚ to 45˚) to further gain airspeed. It was found that the sailplane was stable with good pitch control up to 200 km·h^{-1}. It was challenging to obtain an airspeed higher than 200 km·h^{-1} without the risk of collision with terrain given the hilly environment. The pitch control was, nevertheless, found to gradually lose its authority at airspeed around 230 km·h^{-1} and it was probably attributed to the amount of thrust produced by the V-pitch unit and may be mitigated by either increasing the maximum displacement pitch of the V-pitch or diameter of the propeller. To test this hypothesis, instead of increasing the rotor diameter, the rotor diameter was decreased to 190 mm and the airspeed at which the pitch authority begun to diminish was observed to be around 160 km·h^{-1} which was consistent with the hypothesis. To systematically establish a relationship between the airspeed at which pitch control diminishes and diameter of the propeller, a flight sequence was devised as follow: perform a half roll and dive into headwind at a steep angle (e.g. 20˚) which would result in accumulation of airspeed. Upon reaching certain airspeed, the sailplane would abruptly pitch up (skywards), signifying the lost in pitch control, or for ease of reference, it would be referred to as "roto-stabilizer stall". Figure 4 shows a typical inverted flight scheme used to characterize the stall speed of roto-stabilizer. The instantaneous airspeed as indicated on the NAVGuides is 169 km·h^{-1} with updraft of 18.1 m·s^{-1} and a sink rate of 0.2 m·s^{-1}. Based on this flight sequence a plot was generated. The same test was repeated for canard configuration. The moment arm length was kept constant, except it was now located in front of the CG. No changes were made to the settings of the gyro and the results are summarized in Figure 5. It was observed that the stalling of the roto-stabilizer occurred earlier for the canard configuration compared to the tail-aft configuration for a given diameter of the rotor-stabilizer and that the post-stall pitching only occurred in one direction. Based on these observations, the plausible cause was attributed to the inherent pitching moment of the wing airfoil S3021-095-84.

For validation, the original wing airfoil was changed to symmetrical airfoil NACA 0010 which has no pitching moment. Subsequent simulation runs showed that indeed for both tail-aft and canard configurations, no stalling of the roto-stabilizer was observed for airspeed up to 230 km·h^{-1} with a rotor diameter of only 130 mm. From hereon, the roto-stabilizer implemented in canard configuration will be referred to as roto-canard.

4. Using Roto-Canard to Achieve Ultra-STOL

A distinctive advantage of roto-stabilizer over conventional horizontal stabilizer is that it is able to generate moment in the absence of forward airspeed. In this section, we thus proposed the use of roto-canard to realize ultra-STOL which will particular benefit the emerging field of personal aviation. Figure 6 shows an unmanned canard airplane incorporating the roto-canard concept. The CAD model of the airplane was created using Fusion 360 [10]. It has a wing span of 2000 mm and a fuselage length of about 1145 mm. The wing loading was 73.27

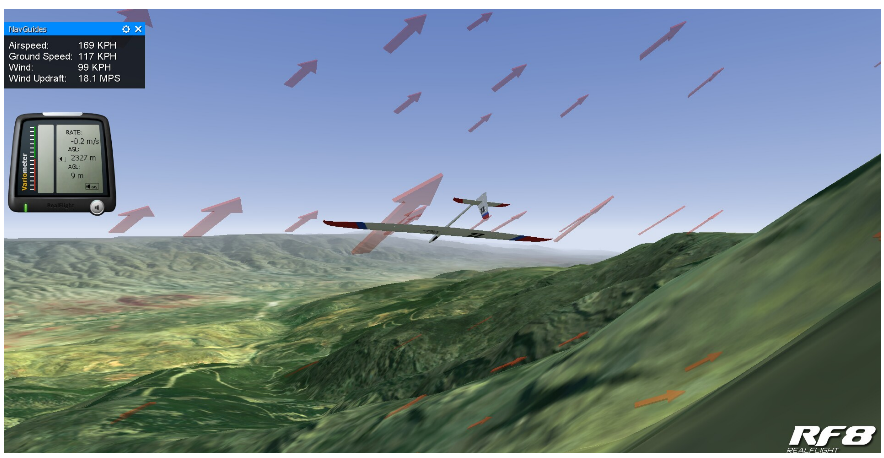


Figure 4. Inverted flight scheme used to characterize the stall speed of roto-stabilizer.

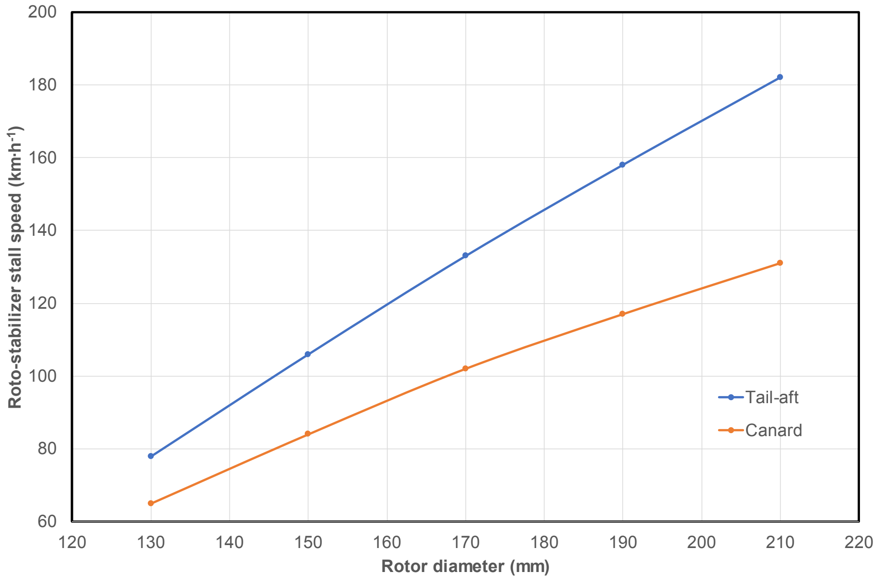
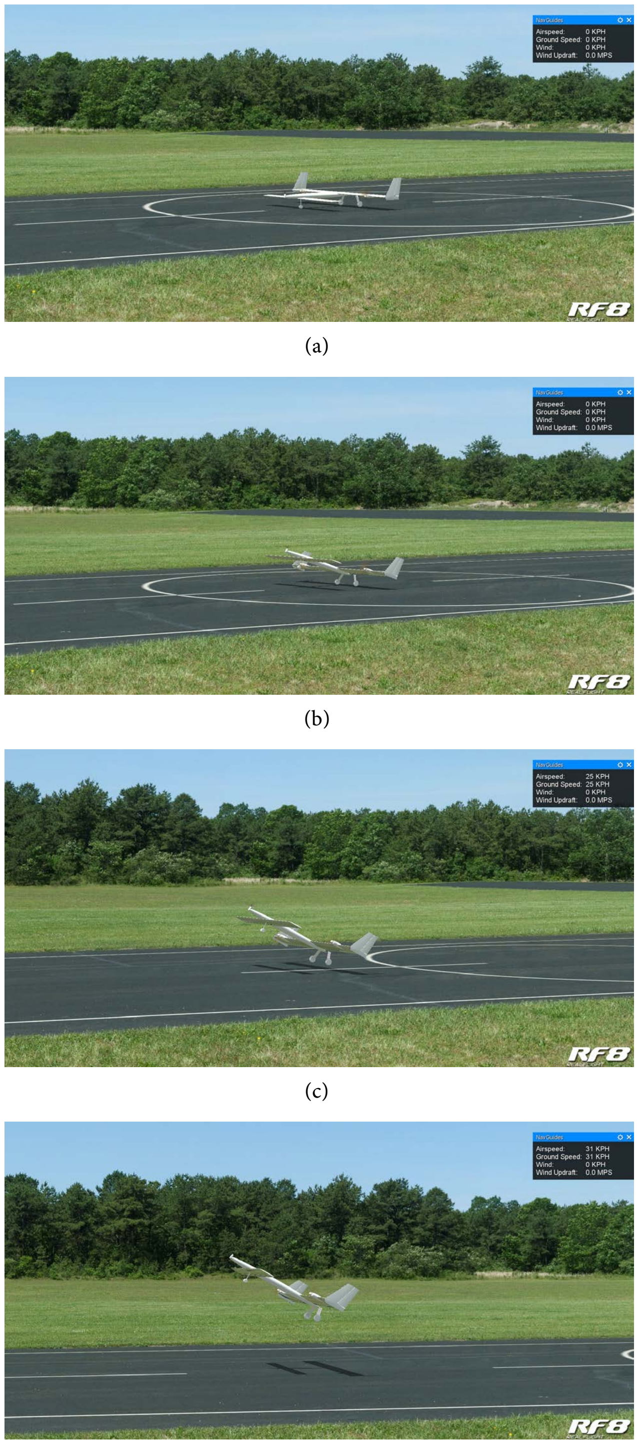


Figure 5. The sailplane's airspeed at which the roto-stabilizer's pitch control diminished as a function of its rotor diameter. The wing airfoil was S3021-095-84.

Figure 6. A canard airplane incorporating the roto-canard concept. The roto-canard was mounted on the nose section which was rotatable about the pitch axis (inset).

g·dm^{-2} which resulted in a nominal stall speed of approximately 43.6 km·h^{-1}. The two main engines produced a total static thrust that significantly exceeded the weight of the aircraft, as typically found in 3D aerobatic airplanes. Differential thrust from the main propellers was used to actuate yaw, especially in the post-stall regime. The roto-canard was mounted on a nose section that was rotatable about the pitch axis (inset). In addition to the roto-canard, the aircraft was equipped with conventional canard with elevator control. The roto-canard enabled the nose of the aircraft to be raisedto establish a high angle of attack, thereby making use of the harrier maneuver to realize the ultra-STOL or even VTOL if the angle of attack were to be further increased to 90˚.

A series of snapshots from a typical ultra-short takeoff sequence is as shown in Figure 7. At the start of the takeoff sequence, the roto-canard raised the nose of



(a)

(b)

(c)

(d)

Figure 7. An ultra-short takeoff sequence typically begun with the nose of the canard airplane raised while the aircraft was stationary on the ground; followed by the commencement of the harrier maneuver.

the aircraft to an angle of approximately 35˚. Note that while in the nose-high attitude, both wind speed and airspeed were zero. With the nose raised, the aircraft initiated the harrier maneuver involving thrusts from the primary propellers. The required ground run distance was only about 3 m, or approximately 3 body lengths. Furthermore, the takeoff airspeed was only 25 $km \cdot h^{-1}$ which was significantly lower than its stall speed (43.6 $km \cdot h^{-1}$) and this is a hallmark of the harrier maneuver. The horizontal acceleration in this case was about 3 $m \cdot s^{-2}$ or 0.31 G. In full scaled aircraft application, such acceleration is expected to be comfortable for the pilot or passengers and hence a viable takeoff method. Once the aircraft has gathered sufficient airspeed, it may revert to conventional canard elevator for pitch control and the rotor-canard may be rotated so that its thrust vector is directed to the front to augment the propulsion. The roto-canard could also serve as a safety redundancy in the event the elevator surfaces are malfunctioned. On the other hand, if the roto-canard were to suffer damage mid-flight, it is possible for the aircraft to make a conventional landing using runway.

The short landing attitude is essentially a descending harrier pass. A video showing the aircraft performing a typical ultra-short landing is available as Video 2 (click on the link to view) at 60% playback speed to enable the landing sequence to be observed more closely. Once the aircraft's main landing gears are on the ground, the nose is gradually lowered. The lowering of the nose angle can take place either in tandem with the deceleration of the aircraft, or after it has come to a halt as shown in Video 2. The distance from the point the main gears touched the ground to a complete stop is about 5.8 m. If desired, shorter ground roll distance could be achieved with higher angle of attack during harrier descent prior to touch-down.

The rotor-stabilizer concept discussed so far is based on variable pitch impeller. It's possible to use opposing pair of fixed pitch impellers as an alternative. However, detailed analysis of which is beyond the scope of this work.

Another important application area that can benefit from the use of roto-stabilizer is severe weather reconnaissance using spinsonde technique [11]. Previous study revealed that a shortcoming associated with spinsonde using flight control surfaces is the inability to quickly arrest the descent at the end of the stall spin, hence making it difficult to safely perform in-situ measurement of the 10-m surface wind which is of interest to meteorologists. Preliminary simulation using the roto-canard aircraft as shown in **Figure 6** suggested that the technique enabled the nose angle of the aircraft to be raised in the midst of a stall spin, and when accompanied by the thrusts from the main propellers aircraft was able to gain altitude while in a stall spin. This novel and exciting ability permits the acquisition of 10-m surface wind and eliminating risk of impact with the surface below. Detailed analysis and characterizations of the advanced spinsonde based on roto-stabilizer approach will be the subject of future work.

5. Conclusion

This work had proposed the concept roto-stabilizer that can be used to substitute conventional horizontal stabilizer whether in tail-aft or canard configuration. The major advantage of the proposed technique is that it is able to exert powerful moment in the absence of airspeed or propeller wash. Proof of concept provided in this simulation study revealed that the roto-stabilizer or roto-canard concept has led to the creation of new maneuvers for aerobatic applications as well as ultra-STOL and VTOL for manned flight. We believed the concept of roto-stabilizer will play an important role in the future of aviation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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