A Comparison of Piloting Technique During Simulated and In-flight Autorotation Manoeuvres

Mushfiqul Alam, Canfield University, Bedford, United Kingdom
Michael Jump, University of Liverpool, Liverpool, United Kingdom

Abstract

This paper compares how pilots perform autorotation manoeuvres during both simulated and real flight tests. Data were collected using the HELIFLIGHT-R simulator with a UH-60-type model, and from flight tests in Bell OH-58 and Bell 206 helicopters. The analysis focused on the flare phase of the manoeuvre, examining how pilots use cyclic and collective controls to manage descent rate, forward speed, and rotor RPM near touchdown. While most pilots followed standard guidance, the study found differences in how the flare was executed. Successful landings were achieved using a range of control techniques, if the pilot timed the flare correctly and coordinated the controls effectively. Less successful landing cases were linked to overly aggressive use of cyclic to reduce forward speed and/or delayed collective use, which made it harder to control the forward speed descent rate. Even minor deviations in timing or control rate can result in unsafe touchdown conditions. The findings highlight the importance of timely and well-matched control inputs during the flare and offer insights for improving training and flight simulation.

NOTATION

Symbols

h	Height above ground, AGL, ft
V_x	Forward speed, kt
V_z	Descent rate, ft/s
θ	Pitch angle, °
X_B	Longitudinal cyclic control input, % (0% = fully forward; 100% = fully aft)
X_C	Collective stick position, % (0% = collective completely lowered, 100% = completely up)

Acronyms

AGL	Altitude Above Ground Level
FAA	Federal Aviation Authority
NRC	National Research Council Canada
RPM	Revolutions Per Minute
TP	Test Pilot
USNTPS	United States Naval Test Pilot School

1. INTRODUCTION

In a conventional helicopter, the autorotation manoeuvre is employed to achieve a safe landing following emergencies such as engine failure or loss of tail rotor effectiveness in Ref 1, 2. However, a number of accidents have occurred during autorotation due to the pilot not timing the control input correct during the manoeuvre. An extreme example would be Ref 3. The autorotation manoeuvre is particularly challenging, as it requires the pilot to perform several coordinated tasks with precise timing.

Autorotation for a conventional helicopter configuration involves a descending flight path, where upward airflow through the rotor system sustains rotor rotation in the absence of engine power. The manoeuvre typically consists of three primary phases: steady-state descent, flare, and landing, see Ref 4. Guidance from the FAA outlines procedures for each of these phases, see Ref 5, 6.

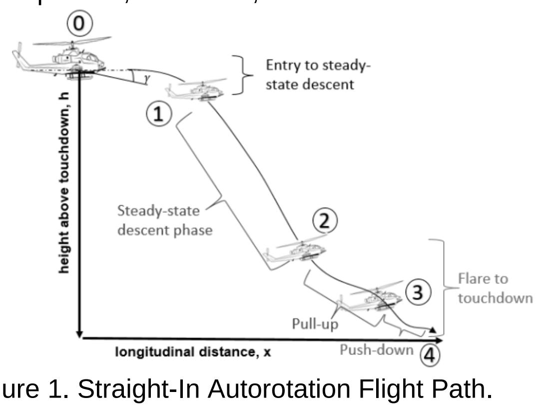


Figure 1. Straight-In Autorotation Flight Path.

Upon experiencing a failure that necessitates autorotation (Figure 1, position 0), the pilot must quickly and fully lower the collective to preserve main rotor speed and apply appropriate pedal input to counter residual rotor thrust. Simultaneously, cyclic inputs must be used to attain the aircraft manufacturer's recommended forward airspeed for autorotation. Once a steady-state descent has been established (Figure 1, position 1), the pilot maintains the appropriate glide speed using cyclic control and adjusts collective as needed to preserve rotor RPM.

At the manufacturer-specified flare initiation altitude (Figure 1, position 2), the pilot applies aft longitudinal cyclic to reduce the rotorcraft's descent rate and airspeed, initiating the flare. Precise execution is critical—an abrupt rearward cyclic input may cause a climb, while a delayed or insufficient flare may fail to sufficiently arrest the descent. As the forward motion decays to the target groundspeed (Figure 1, position 3), the pilot moves the cyclic forward to set the landing attitude, then allows the helicopter to descend vertically (Figure 1, position 4), applying collective as necessary to cushion the landing.

The University of Liverpool recently completed a research project which aimed to explore novel methods to assist pilots in executing successful autorotation manoeuvres. As part of this effort, a comprehensive dataset was collected, comprising both real-world and simulated autorotation flight test points. In-flight data were provided by the United States Naval Test Pilot School (USNTPS), using the Bell OH-58 Kiowa, and the National Research Council (NRC) Canada's Flight research Laboratory (FRL), using the Bell 206B JetRanger. Piloted simulation autorotations were conducted at the University of Liverpool in the HELIFLIGHT-R full-motion simulator (Ref 7) using a non-linear rotorcraft dynamics model developed using FLIGHTLAB, see Ref 8, broadly representative of a UH-60 Black Hawk.

Analysis revealed that while pilot behaviour generally aligned with FAA guidance, both similarities and key differences emerged between the piloting techniques employed in flight and in simulation. This paper presents a detailed comparison of these techniques, offering insight into the underlying causes of divergence and implications for pilot training and simulation fidelity.

The authors have published previous work that has analysed the autorotation manoeuvre in terms of the efficacy of the novel autorotation guidance solutions tested in Refs 9-11, and algorithms developed in Refs 4, 9-13. This is the first paper to specifically investigate piloting technique and the similarities and differences between in-flight and simulated test points.

The remainder of the paper is structured as follows: Section 2 describes the data acquisition process for both simulated and flight-tested autorotation manoeuvres. Section 3 outlines the criteria used to assess whether a touchdown was survivable. Sections 4 and 5 present the analysis results from the simulation and real flight tests, respectively. Section 6 discusses the key findings and comparisons across both datasets, and Section 7 concludes the paper.

2. AUTOROTATION DATA ACQUISTION

2.1. In-flight test data

Two sources of in-flight test data were analysed in this study. The first set comprised autorotation manoeuvres performed using the USNTPS Bell OH-58 Kiowa helicopters. These manoeuvres were conducted opportunistically, meaning that they were not part of a dedicated flight test campaign but were performed during scheduled sorties with other objectives, when time and conditions permitted. As a result, a total of 18 autorotation datasets were obtained. Due to the ad-hoc nature of these flights, the initial conditions—such as entry altitude, airspeed, and descent profile—exhibit some variability across the dataset. These manoeuvres were flown all of the way to the ground.

The second set of flight data was collected using the Bell 206B JetRanger operated by the NRC FRL. Multiple autorotation flights were conducted to demonstrate autorotation. The manoeuvre commenced at 1500 ft at 70 kt. It is important to note that the Bell 206 pilots did not make a touchdown to the ground, they instead autorotated to a simulated touchdown at 400 ft AGL.

2.2. Simulated flight test data

Simulated pilot-in-the-loop autorotation test campaigns were conducted using the University of Liverpool's HELIFLIGHT-R full-motion simulation facility, see Ref 7 (Figure 2). These tests employed a medium/high-fidelity, non-linear rotorcraft flight dynamics model developed in FLIGHTLAB, representative of a generic utility-class helicopter with characteristics like the Sikorsky UH-60 Black Hawk – the FLIGHTLAB Generic Rotorcraft (FGR), see Ref 8. Unlike the OH-58 and Bell 206, which employ skids as landing gear, the FGR has main, and tail wheels modelled for the landing gear. Engine failure was simulated by disengaging the clutch from the main rotor in the helicopter model, with a representative engine sound change. The tests were conducted with the 6 degree-of-freedom generic full motion filters enabled.

Figure 2. HELIFLIGHT-R flight simulator.

A total of five professional TPs participated in the simulation trials. TP1 and TP3 are former Royal Air Force helicopter squadron pilots and previously served as tutors and squadron commanders at the Empire Test Pilots' School (ETPS). TP2 and TP5 are former Royal Navy rotary-wing pilots, both ETPS graduates. Both have recently retired from a national flag-carrier airline. TP4 is a former Royal Air Force rotary-wing pilot, a graduate of the École du Personnel Navigant d'Essais et de Réception (EPNER) and previously served as an experimental test pilot for offshore helicopter operations.

To try to ensure repeatability and consistency across simulated flight trial test points, the initial conditions for all simulated autorotation manoeuvres were standardised. Each manoeuvre commenced from a trimmed, straight-and-level flight condition at 1000 ft altitude and a forward speed of 80 knots (the recommended flight manual speed for the modelled aircraft mass). Engine failure was simulated by disengaging the clutch from the main rotor system within the helicopter dynamics model.

3. AUTOROTATION MANOEUVRE PERFORANCE FOR REAL AND SIMULATED CONDITIONS

3.1. Touchdown Performance

The touchdown performance was assessed using the forward velocity and descent rate for each of the autorotation maneuvers performed. Table 1 and Table 2 show the performance criteria applied for the results presented below. The criteria of Table 1 are those used throughout the study and were first published in Ref 14, 15. Both sets of criteria were established based upon discussions with the project test pilots. For the case of simulated flights, pilots were 'allowed' more relaxed limits for forward velocity and descent rate (a) because the pilots were tasked with landing on a runway and hence sometimes elected to perform a 'roller landing' i.e. landed in a manner more consistent with a fixed-wing aircraft and (b) during the initial work-up to the trials, the pilots reported that heave visual cueing in the simulator was somewhat limited.

Table 1. Conditions for Successful and Marginal Touchdown Performance for simulated flight test.

Parameter	Condition for desirable landing	Condition for adequate landing
Pitch Angle, θ	< 12^o	< 20^o
Forward Velocity	< 30 knots	< 60 knots
Descent Velocity	< 8 ft/s	< 15 ft/s
Pitch Rate, q	-30 ^{o}/s < q < 20 ^{o}/s	-50 ^{o}/s < q < 20 ^{o}/s

Table 2. Conditions for Successful and Marginal Touchdown Performance for in flight test.

Parameter	Condition for desirable landing	Condition for adequate landing
Pitch Angle, θ	< 12^o	< 20^o
Forward Velocity	< 25 knots	< 30 knots
Descent Velocity	< 5 ft/s	< 6 ft/s
Pitch Rate, q	-30 ^{o}/s < q < 20 ^{o}/s	-50 ^{o}/s < q < 20 ^{o}/s

Any touchdown performance outside the boundaries defined in Table 1 and Table 2 were categorized as "Unsuccessful".

3.1.1. Touchdown performance for simulated flight test points

Figure 3 presents a summary of the descent rates and forward velocities achieved for all the simulated autorotation runs for the five TPs. The touchdown of the rotorcraft was identified using the Weight on Wheel (WoW) parameter within the FGR model. It was assumed that the touchdown had occurred whenever the WoW was flagged as “ON” for the first time. All of the simulated test points met the criteria for pitch rate q and angle θ for all TPs. Hence, the performance zones are categorized as "Desirable", "Adequate", and "Unsuccessful" based on descent rate and forward velocity thresholds at touchdown alone.

It can be seen from Figure 3 that most of the TPs in the simulator achieved marginal landing performance. However, TP2 largely achieved a successful landing performance.

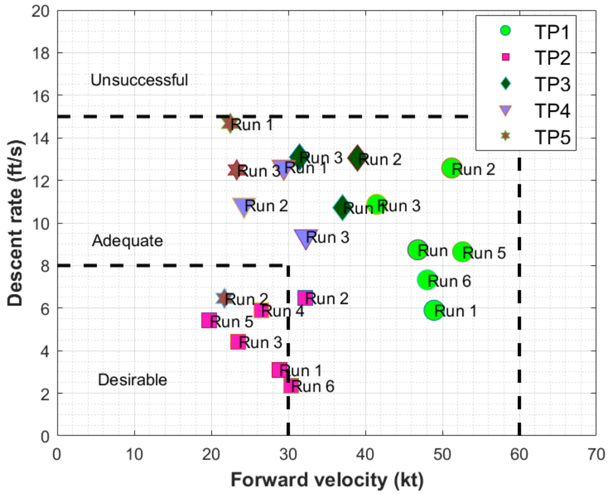
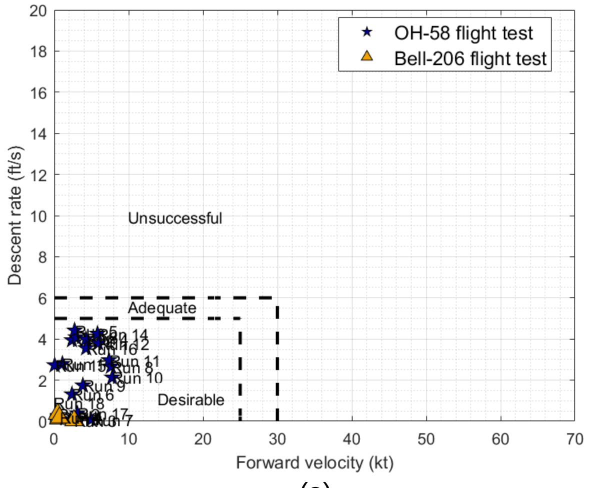


Figure 3. Touchdown performance of simulated flight.

TP1 consistently achieved landing with a high forward speed (~50 kt) but managed to reduce the descent rate below 9 ft/s. TP2 maintained very low descent rates across most runs, even at relatively low forward velocities (~20–30 kt) managing to make a desirable touchdown. TP3 managed to reduce the forward speed landed with high descent rates, making all his landings marginal. TP4 managed to reduce the forward speed to a greater degree than TP3. However, TP4 landed with higher descent rates. TP5 managed to reduce the forward speed below the desired speed (30 kt). However, he landed with a high descent rate making the overall landing assessment as adequate. The exception is Run 2, where he managed to control both forward speed and descent rate within the desirable limits.

3.1.2. Touchdown performance for in-flight test points

Figure 4 presents the touchdown performance analysis from the in-flight autorotation test points, again showing descent rate versus forward velocity at touchdown. The touchdown of the OH-58 Kiowa was detected manually, by considering when the vertical acceleration a_z starts to oscillate abruptly towards the end of the manoeuvre indicating touchdown. The airspeed data obtained from the flight test contained a component of the wind velocity. The wind velocity was estimated by taking the average value of the airspeed reading following the touchdown for each run. To obtain the ground speed at touchdown, the average wind speed was subtracted from the airspeed.



(a)

(b) Zoomed in for clarity.

Figure 4. Touchdown performance of real flight.

All touchdowns fall within or near a nominal performance envelope (bounded by ~5 ft/s descent rate and ~10 kt forward velocity). For the in-flight test points, pilots generally achieved low descent rates and low ground speeds at touchdown. OH-58 pilots displayed a wider spread in both parameters, particularly forward velocity (~2–10 kt). Bell 206 pilots had consistently low forward velocities (<5 kt) and descent rates (<2 ft/s).

The FRL data show highly consistent touchdown parameters. The USNTPS data, collected opportunistically during routine sorties, exhibit lower variability in both descent rate and forward speed compared to simulator results (Figure 3).

4. ANALYSIS OF AUTOROTATION MANOEUVRES UNDER SIMULATED CONDITIONS

4.1. Longitudinal states during the autorotation

A representative sample of the longitudinal states of the helicopter during autorotation obtained from the simulation data is shown in Figure 5 for all the TPs. During the simulated trials, TPs were asked to comment on entry to the different flight phases during the flight. Different flight phases were thus identified from the pilot's comments (discussed in detail in Section 4.3 and 4.3). The x-axes of the plots are labelled as 'Time to go' meaning that $t = 0$ is the time at touchdown. Therefore, 'negative' time indicates the remaining task time until touchdown.

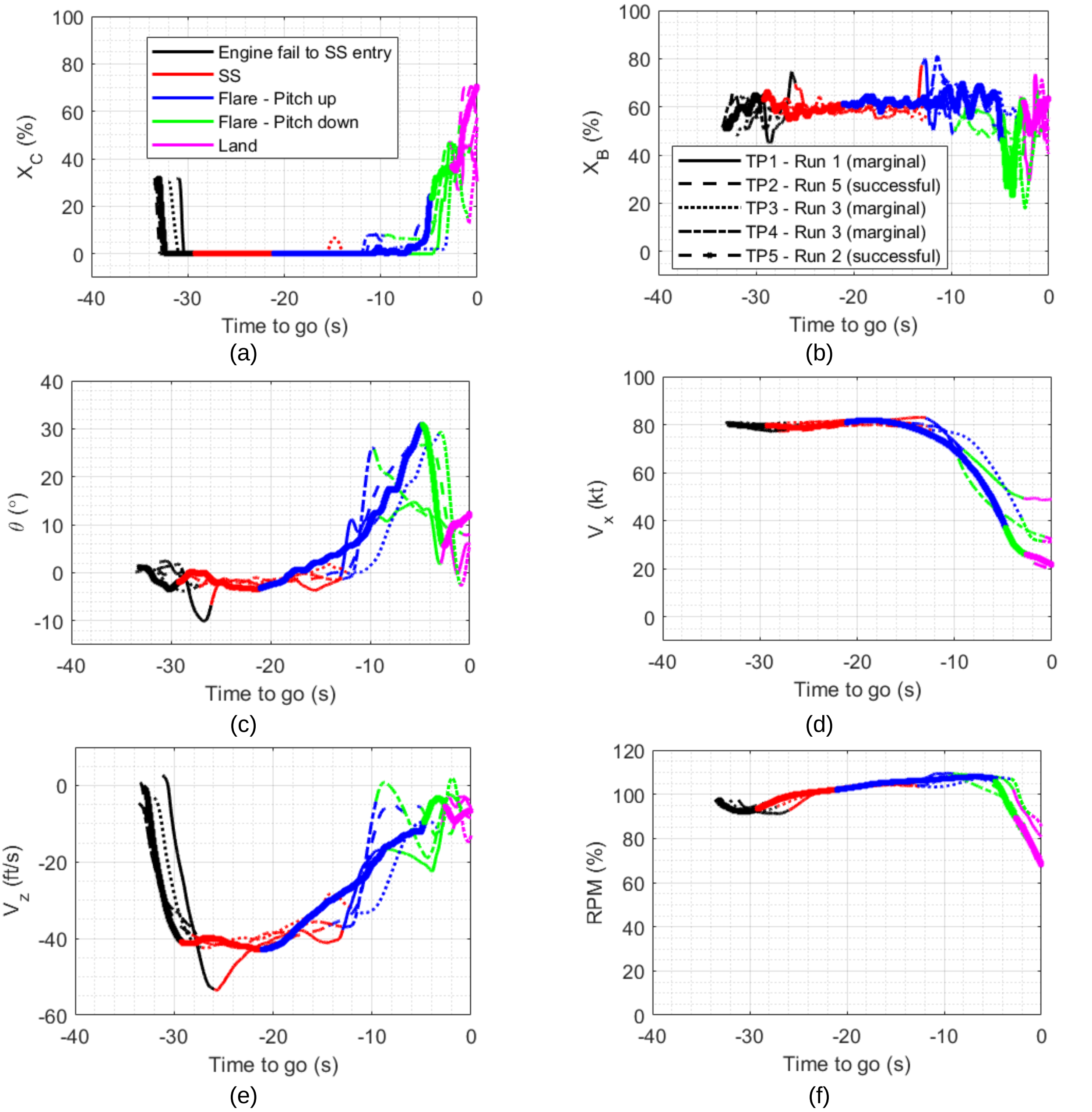


Figure 5. Representative longitudinal states during simulated autorotation.

After identifying the simulated engine failure, the pilot lowers the collective (X_C, Figure 5a) and uses the aircraft's longitudinal cyclic (X_B. Figure 5b) to adjust the pitch attitude (θ, Figure 5c) in order to achieve a desired forward velocity (V_x, Figure 5d). This phase of the manoeuvre is the entry to steady state following engine failure (positions 0 to 1 in Figure 1, marked in black in Figure 5). The desired autorotation speed depends on the helicopter model and pilot. For example, the recommended autorotation forward speed for the UH-60 for minimum descent rate or maximum time to descend is 80 kt, see Ref 16, 17, hence the pilots were aiming to stabilize the forward speed at 80 kt, see Figure 5d.

Once the rotorcraft achieves the desired forward speed, the rate of descent also stabilizes, depending on the chosen forward speed, see Figure 5e. During this steady state phase, the pilot attempts to maintain the recommended airspeed until entry to the flare phase of the manoeuvre (positions 1 to 2 in Figure 1, marked in red in Figure 5). During the steady-state descent, the pitch angle (θ) remains approximately constant until the entry to flare phase of the flight, see Figure 5c. In this phase the pilots also aim to maintain main rotor RPM at ~100%, Figure 5f.

At the end of the steady-state descent (Position 2 to 3 in Figure 1), the pilots initiate the flare phase of the manoeuvre to reduce the forward velocity and descent rate by pulling back on the longitudinal cyclic (X_B, Figure 5b), marked in blue in Figure 5. This causes the helicopter to pitch up, Figure 5d, causing the main rotor speed to increase, Figure 5f. This condition is held for a short time to allow the descent rate and forward speed to reduce/decay, Figure 5d and Figure 5e. During this time the main rotor over speeds beyond 100%, Figure 5f. This is considered to be acceptable in an emergency situation such as an autorotation.

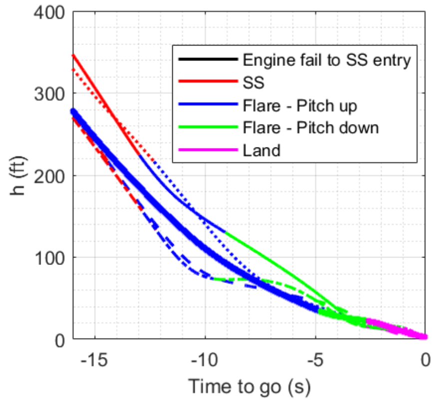
The pilot then increases the collective X_C to maintain the RPM, see Figure 5a. Specifically, TP2 and TP5 applies a notional "step input" (sometimes called a 'check', Ref 1) to the collective input (discussed further in Section 4.3), to prevent the rotor speed from increasing too much. Prior to touchdown, the pilot reduces the helicopter's pitch to a level attitude by moving the longitudinal cyclic forward (Figure 5b); this causes a slight increase in the descent rate (Position 3 to 4 in Figure 1, marked in green in Figure 5e). at approximately the level attitude, the pilot initiates the touchdown phase of the manoeuvre. As the nose is lowered and the aircraft begins to descend towards the ground, the pilot gradually pulls on the collective (X_C, Figure 5a), further reducing the descent rate to cushion the final touchdown (Position 4 to 5 in Figure 1, marked in magenta in Figure 5), causing the main rotor speed to decay further.

It is evident that the flare phase represents the most dynamic portion of the autorotation sequence. Rapid changes in pitch attitude, and main rotor speed occur over a short time span, requiring precise timing and coordination from the pilot.

To better understand pilot behaviour during this critical period, a focused analysis of the flare phase is presented in the following section.

4.2. Pilot Technique and Aircraft Response in the Flare Phase – Simulated Flight

Figure 6 shows the final 16 seconds of the trajectories shown in the previous section.



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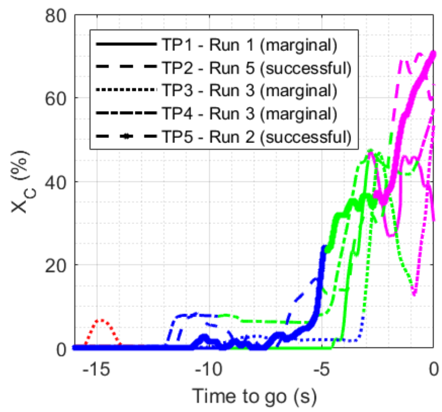

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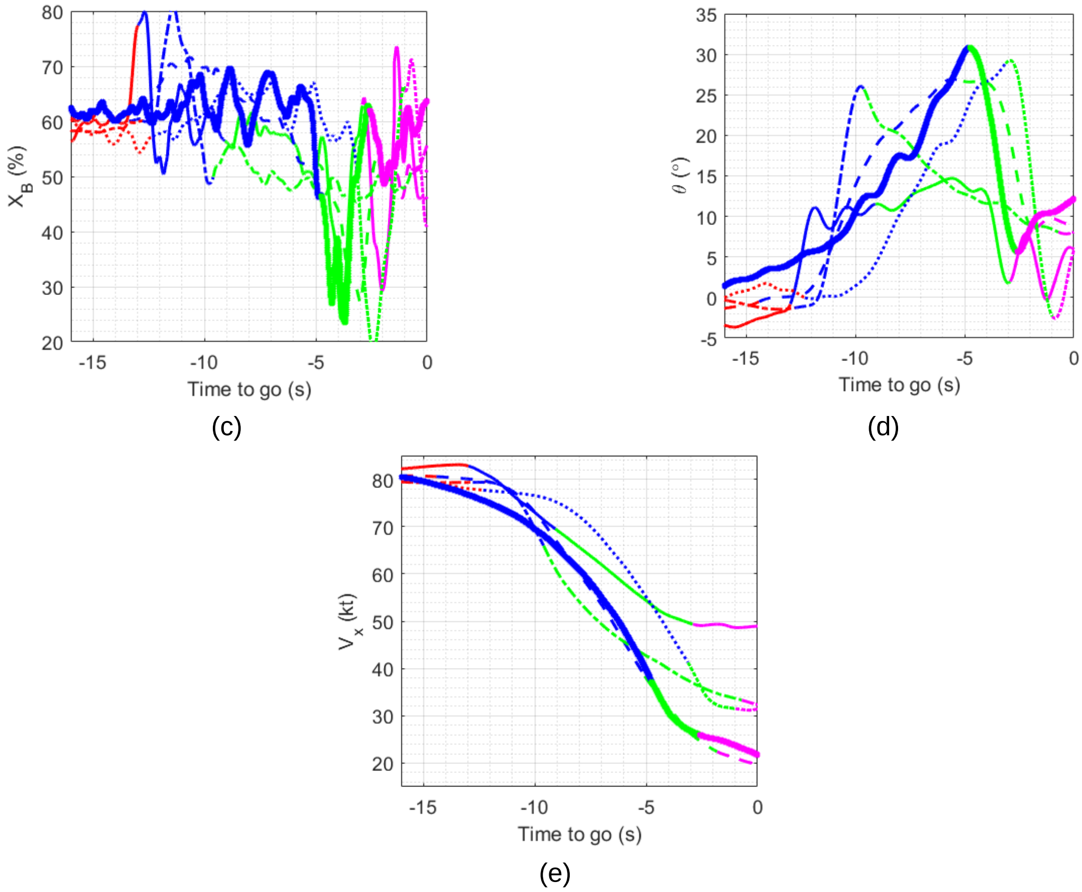


Figure 6. Final 16 seconds in trajectory during the flare phase of the simulated autorotation.

According to UH-60 flight manual, the recommended flare initiation altitude is between 150 and 200 ft. This flare height criterion as well as touchdown metrics from Table 1 are shown in Figure 7 for each TP. In the simulated trials, test pilots TP1 through TP4 initiated the flare manoeuvre within this recommended range, with flare onset occurring at approximately 150–220 ft (indicated by the start of the blue marker in Figure 6a).

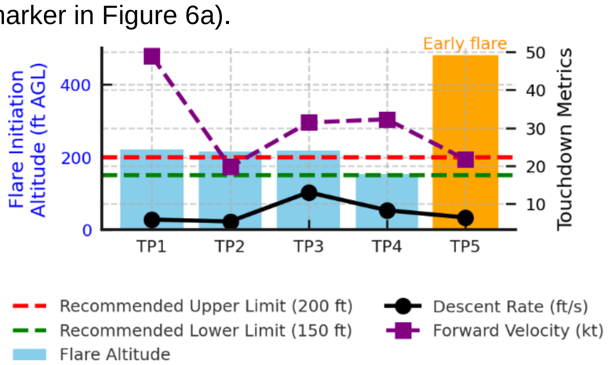
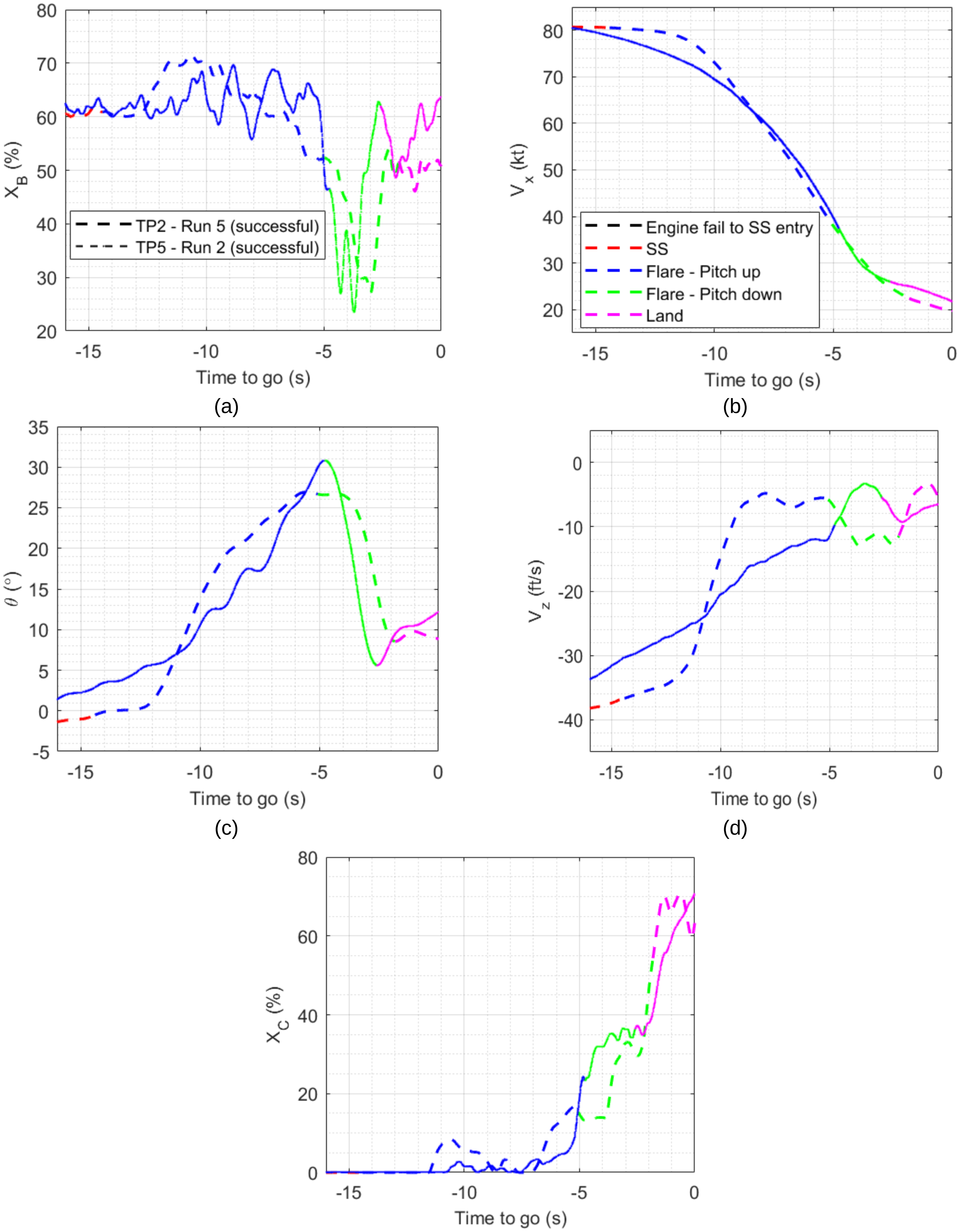


Figure 7. Flare initiation altitude and touchdown performance.

TP1 had a controlled descent rate but very high forward speed (~49 kt) — potentially a fast run-on landing. TP3 had the highest descent rate, indicating a harder landing despite a mid-range forward velocity.

TP2 had both low descent rate and low forward velocity — a textbook autorotation landing outlined in the FAA outlined procedures in Ref 5, 6. TP5, despite an early flare, achieved acceptable descent and forward speeds — though the technique diverged from standard. TP5, despite initiating the flare much earlier than recommended, still achieved a successful landing, as did TP2, who followed standard flare timing. This suggests that pilot's techniques vary and that different strategies yield different outcomes; this requires further investigation and is shown in what follows.



(e)

Figure 8. Piloting comparison of TP2 and TP5

4.3. Successful landing by Test Pilot 2 and 5

TP2's entry into the flare was aggressive, marked by a larger and more rapid aft longitudinal cyclic input (X_B, Figure 8a) compared to TP5, resulting in a rapid pitch-up motion and swift attainment of the maximum pitch attitude θ, Figure 8c. This aggressive control action enabled TP2 to reduce forward velocity (V_x) more quickly during the flare compared to TP5, Figure 8b. In contrast, TP5 applied a more gradual and gentler X_B input, resulting in a smoother pitch-up trajectory and a slower transition to maximum pitch angle (θ), see Figure 8c.

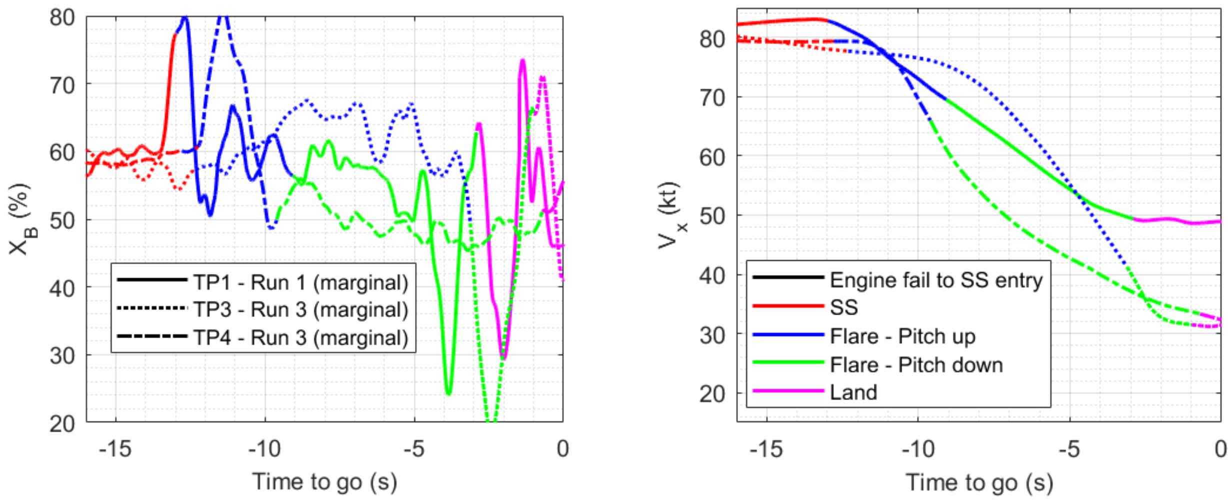
In their earlier work in Ref 11, 12, the authors illustrated that, unsurprisingly, the reduction of V_x during the pitch up motion in the flare phase is related to the maximum pitch angle achieved and duration it takes to achieve that maximum pitch angle. A greater decay in V_x is possible by increasing both the maximum pitch angle and duration to achieve it.

Once the maximum pitch attitude was reached, both TP2 and TP5 began the levelling-off phase by applying forward cyclic input (X_B), the green section in Figure 8a, to level the aircraft and achieve the desired forward velocity (V_x) for touchdown. TP2 required approximately 3.5 seconds to complete this pitch-down transition, whereas TP5 executed a more aggressive forward cyclic input, levelling the aircraft in about 2 seconds, see Figure 8c. During this phase—highlighted in green in the plots—it can be seen that TP2's vertical speed (V_z) began to increase, indicating a higher descent rate compared to TP5, see Figure 8d. This difference is attributable to collective input behaviour: as shown in the X_c plot in Figure 8e, TP5 applied a higher collective input than TP2 during this period, helping to better arrest the rate of descent while the nose-down attitude was being established. Once the aircraft was levelled, both TP2 and TP5 applied maximum available collective input (X_c, see Figure 8e, magenta coloured section of the data), to arrest the remaining descent and cushion the landing. This final collective input ensured that both pilots achieved acceptable touchdown conditions despite employing different flare strategies.

4.4. Marginal landing by Test Pilot 1, 3 and 4

Figure 9 illustrates representative flight trajectories for marginal autorotation landings performed by TP1, TP3, and TP4. These cases demonstrate successful control of certain flight parameters, while others remained outside of the desirable touchdown criteria.

TP1 entered the flare from an initial pitch attitude of approximately -3^o and a slightly higher forward velocity of ~83 kt (Figure 9b, c) compared to 80 kt. The flare was initiated gently, with a gradual increase in longitudinal cyclic input (X_B, Figure 9a), leading to a maximum pitch angle of ~13^o. It took about 4 seconds to reach this peak, followed by another 5 seconds to level the nose of the aircraft (blue and green regions in Figure 9c). Due to this low maximum pitch angle, the forward velocity (V_x) decreased only modestly—from 83 kt to 49 kt—which remained above the acceptable range for autorotation landings. During the flare, TP1 did not apply a step collective input (X_C), commonly referred to as a "check", to manage rotor speed, see Figure 9d. Consequently, the main rotor RPM increased to 110% (Figure 9f). As the aircraft's nose was levelled (~4 seconds before touchdown), vertical speed (V_z) began to increase, see Figure 9e. In response, TP1 gradually applied full collective input, cushioning the landing and achieving an acceptable descent rate. However, the high residual forward velocity resulted in a marginal landing outcome.



(a) (b)

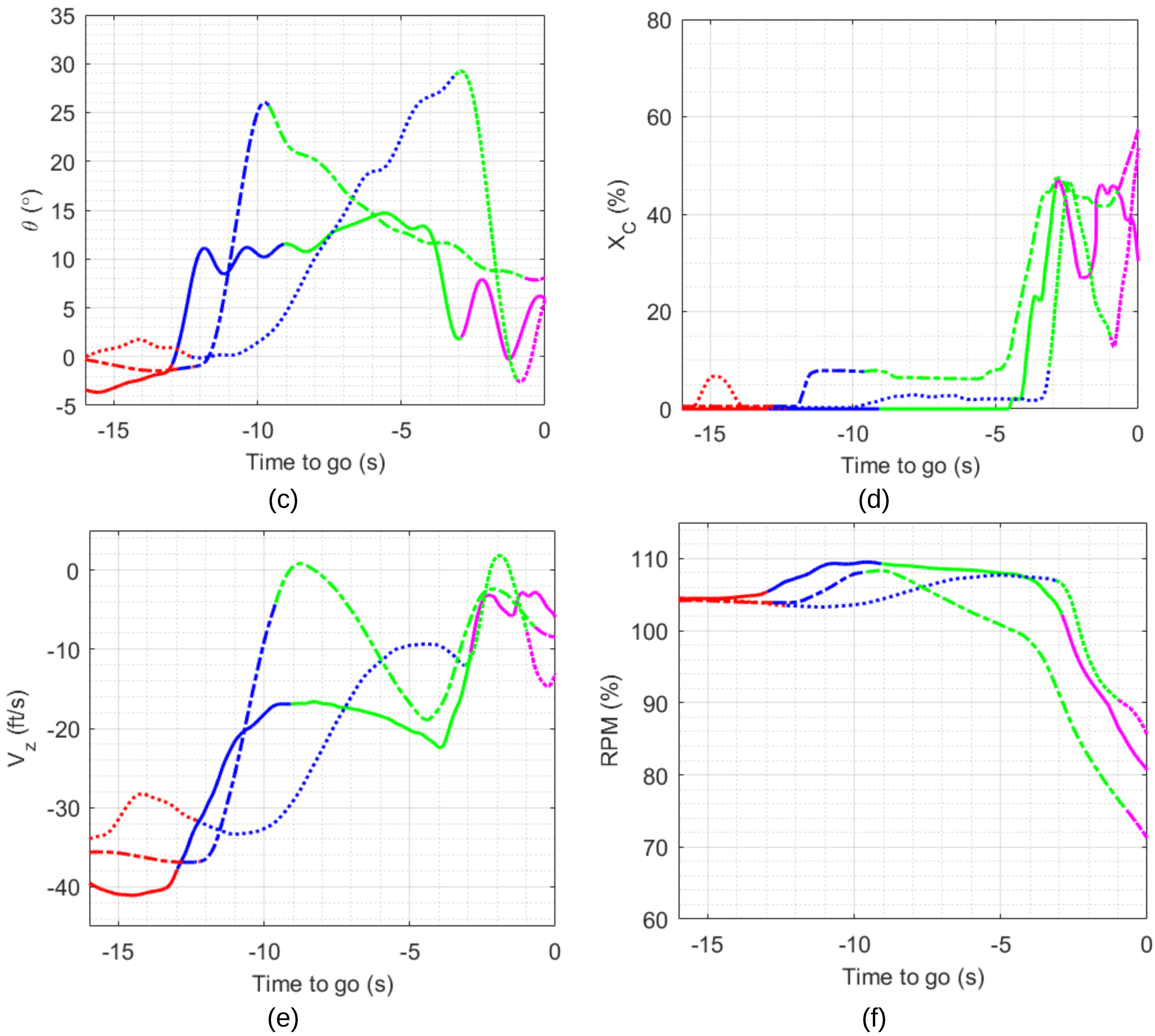


Figure 9. Piloting comparison of TP1, TP3 and TP4.

TP3 initiated the flare with a strong aft cyclic input (X_B), holding the control in the aft position for approximately 9 seconds (Figure 9a), which resulted in a maximum pitch angle of ~29^o (Figure 9c). Upon reaching this peak, TP3 quickly levelled the aircraft with an aggressive forward cyclic input, completing the pitch-down phase in about 2 seconds (green region, Figure 9a, c).

During this transition, TP3 did not use a step input in X_c to manage rotor RPM. Instead, he gradually increased the collective to control descent. Around 1.5 seconds before touchdown, a "ballooning" effect occurred: the aircraft briefly began climbing, evidenced by a positive V_z (Figure 9e). To counteract this, TP3 abruptly lowered the collective (notable drop in X_C between -3 and -1 seconds in Figure 9d), increasing the descent rate. Once the descent resumed, the collective was gradually increased again to cushion the landing.

While TP3 successfully reduced forward velocity, the overcompensation during ballooning resulted in a less controlled vertical speed near touchdown, categorizing this landing as marginal.

TP4 initiated the flare with an aggressive aft cyclic input, causing the pitch angle to rapidly increase and reach its maximum within ~1.5 seconds (Figure 9a, c). He then levelled the nose gradually over ~9 seconds using gentle forward cyclic input, reducing V_x to ~ 30 kt. To manage rotor RPM, TP4 applied a notional step input in X_C. However, this step was ~42% of the total range (Figure 9d), significantly higher than the 15% used by TP2 (Figure 8e). As the levelling phase concluded, TP4 gradually increased X_C to a maximum of ~58%, cushioning the aircraft to a vertical speed of ~8.43 ft/s at touchdown.

It could be argued that TP2 and TP4 both applied a similar final collective input—approximately 60%—yet only TP2 achieved a vertical speed (V_z) within the acceptable limits. The key difference lies in their rotor RPM management during the flare phase.

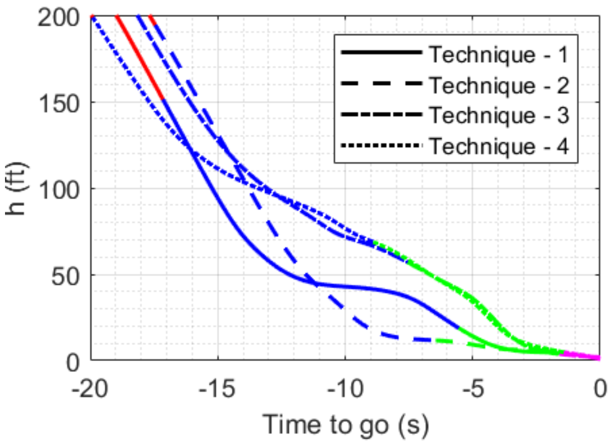
TP4 applied a larger step input of ~42% in collective (X_C) to manage rotor RPM, which caused a rapid decay in rotor speed. In contrast, TP2 applied a more modest check input of ~15%, allowing the rotor RPM to remain higher for a longer duration. This difference had a direct impact on rotor efficiency during the final stages of descent, meaning when the RPM drops—due to high collective input or poor timing—the rotor blades have less kinetic energy, so they generate less lift for the same collective input.

In TP4's case, the premature loss of rotor RPM reduced the effectiveness of the main rotor in generating thrust. This required greater effort in X_C to achieve comparable cushioning. Consequently, TP4's descent rate remained marginally above the acceptable threshold, highlighting the critical role of precise rotor energy management in achieving a successful autorotation landing.

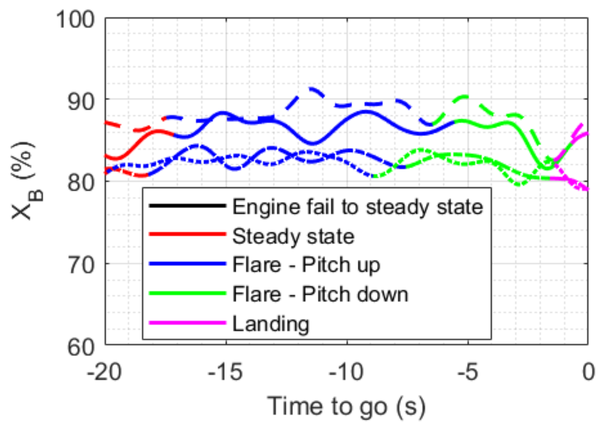
5. ANALYSIS OF AUTOROTATION MANOEUVRES for REAL FLIGHT TEST POINTS

5.1. Pilot Technique and Aircraft Response in the Flare Phase – OH-58

The first two phases (engine fail to steady state, and steady state) in the flight test data was similar in all 18 runs. Therefore, the analysis focused primarily on the flare to touchdown phases of the flight. The OH-58 data for autorotation manoeuvres reveal four distinct piloting techniques, each employing different control strategies during the flare phase. Figure 10 presents the final 20 seconds of flight for each case.



(a)



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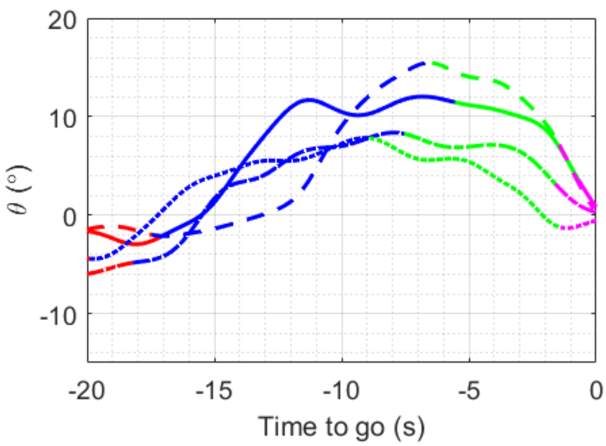

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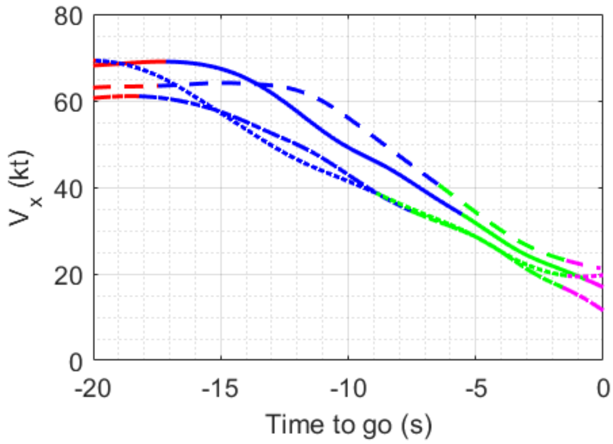
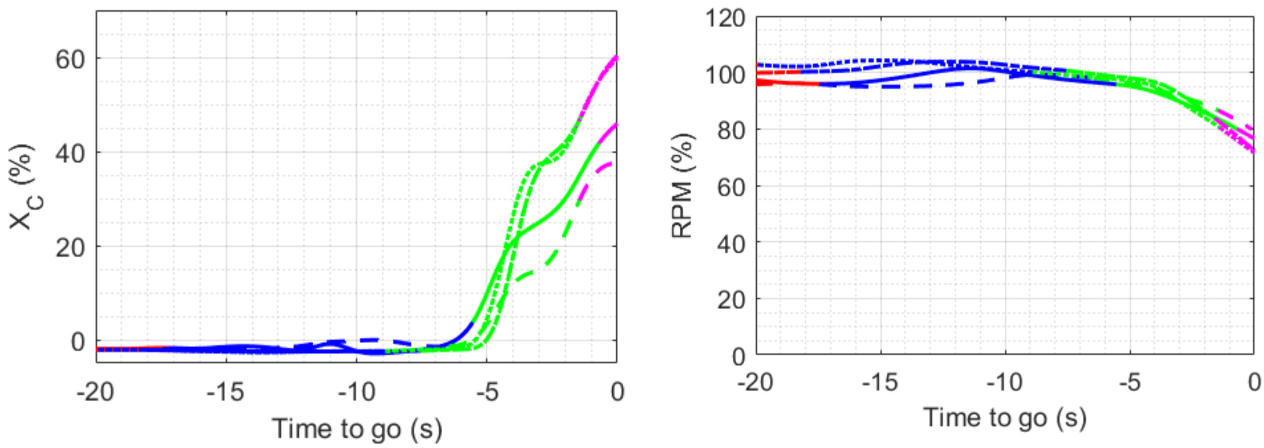


(d)



(e) (f)

Figure 10. Final 16 seconds in trajectory during the flare phase of the in-flight test autorotation using OH-58.

Technique 1 initiated the flare at an altitude of approximately 150 ft AGL and a forward velocity of ~70 kt, see Figure 10a, d. The pilot gradually applied aft longitudinal cyclic input (X_B) to increase the aircraft pitch angle (θ) to a maximum of ~11°, holding this attitude to reduce forward speed, see Figure 10c, d. The pitch-up phase lasted approximately 12 seconds, followed by a 4-second pitch-down. During this transition, the pilot applied a gentle step input of ~20% collective (X_C) to maintain rotor RPM, see Figure 10e, f. The collective was then gradually increased to cushion the landing, with rotor RPM maintained close to 100% throughout. This technique reflects a cautious, energy-preserving strategy, prioritizing rotor RPM stability over aggressive deceleration.

Technique 2 began the flare at an altitude of ~180 ft and a forward velocity of ~62 kt. Compared to Technique 1, this pilot applied a slightly more aggressive cyclic input, see Figure 10b, resulting in a maximum pitch angle of ~15°, see Figure 10c. The pitch-up phase lasted ~10 seconds, followed by ~4 seconds to level the nose. A 15% collective step input was used during the pitch-down phase to preserve rotor RPM, see Figure 10e, f. The rotor speed remained within acceptable bounds. This approach achieved a balanced trade-off between forward speed reduction and vertical descent control.

Technique 3 initiated the flare at ~200 ft AGL and ~60 kt forward velocity, see Figure 10a, d. The pilot employed a gentle flare, increasing the pitch angle to ~9° over a 12-second pitch-up phase, followed by a 6-second pitch-down, see Figure 10c. To control rotor speed during the transition, the pilot applied a larger step input of ~40% collective, see Figure 10e. After a level attitude was achieved, the collective was gradually increased to cushion the descent. This technique demonstrated conservative pitch control with a heavier reliance on collective to manage energy during the terminal phase.

Technique 4 also began the flare at ~200 ft AGL, with a forward velocity of ~70 kt, see Figure 10a, d. Like Technique 3, the pilot used a gentle cyclic input to achieve a maximum pitch angle of ~9°, see Figure 10c. However, the pitch-up phase was extended to ~12 seconds, and the pitch-down phase lasted ~8 seconds—the longest of the four. This prolonged flare allowed the pilot to reduce forward velocity significantly, from ~70 kt to ~20 kt, offering the most effective deceleration. A ~40% collective step input was used during the pitch-down to maintain rotor RPM, see Figure 10e, f.

5.2. Pilot Technique and Aircraft Response in the Flare Phase – Bell 206

Figure 11 presents the final 15 seconds of the autorotation manoeuvre performed in the Bell 206 rotorcraft focusing on the flare phase of the flight. For this analysis, it is assumed that the pilots aimed to achieve level flight at an altitude of 400 ft AGL, and the touchdown point corresponding to 400 ft altitude has been referenced as 0 ft AGL for height measurements.

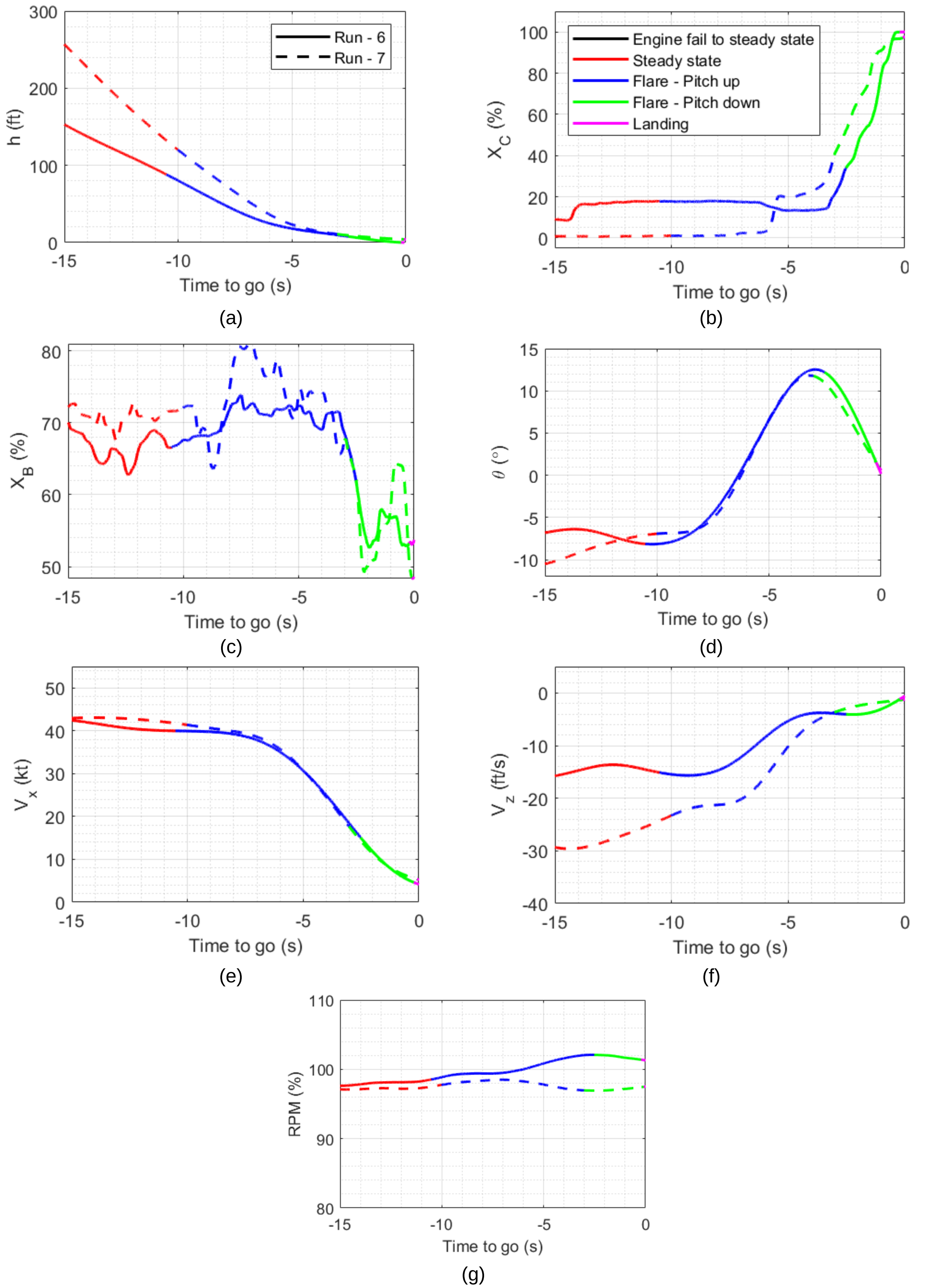


Figure 11. Final 16 seconds in trajectory during the flare phase of the in-flight test autorotation using Bell 206.

The Bell 206 autorotation data from Runs 6 and 7 illustrate two distinct yet effective flare techniques, both resulting in controlled and safe 'touchdown' conditions.

In Run 6, flare initiation occurred at an altitude of approximately 88 ft and a forward velocity of ~43 kt, see Figure 11a, e. The pilot applied a smooth and progressive longitudinal cyclic input (X_B), inducing a steady pitch-up to a maximum pitch angle of ~13.5° over a duration of roughly 6 seconds, see Figure 11c, d. This was followed by a controlled pitch-down phase lasting ~3 seconds, during which the aircraft was levelled for touchdown. Notably, the pilot applied a sustained 20% step input in the collective (X_C) for nearly 10 seconds, helping to maintain rotor RPM near 100%, see Figure 11b. In the final moments before touchdown, the collective was increased sharply from ~20% to 100%, cushioning the descent. Throughout the flare, the forward velocity (V_x) decreased significantly, and the vertical speed (V_z) remained within acceptable limits. The pilot transitioned smoothly from the pitch-down phase to the final touchdown, using well-timed control inputs to maintain rotor speed and achieve a controlled landing.

By contrast, Run 7 featured a slightly earlier flare initiation, at an altitude of ~120 ft, also at ~43 kt forward velocity, Figure 11a, e. The pitch-up response was more gradual, with the aircraft reaching a maximum pitch angle of ~12°. The longitudinal cyclic input (X_B) was applied more gently compared to Run 6, while the collective input (X_C) was applied more assertively. In this case, the collective build-up began only ~3 seconds prior to touchdown, with the pilot again applying a 20% step input to manage rotor speed. Rotor RPM remained well-regulated between 98% and 101%, and the vertical speed showed a smooth decay from ~–30 ft/s to near zero.

6. DISCUSSION PILOTING TECHNIQUE DURING AUTOROTATION MANOEUVRES

6.1 Piloting techniques in simulated flight test points

The analysis of simulated autorotation landings revealed a range of piloting techniques, each influencing landing success in distinct ways. TP2 demonstrated a textbook approach, initiating the flare at ~200 ft with aggressive cyclic input, achieving both effective deceleration and descent rate control. TP5, though initiating flare significantly earlier (~470 ft), executed a gradual cyclic strategy and used higher collective input during the flare recovery, ultimately achieving a similarly successful landing—highlighting that both standard and alternative strategies can yield acceptable outcomes if well-executed.

In contrast, TP1, TP3, and TP4 produced marginal landings due to trade-offs in control input timing or rotor energy management. TP1's gentle flare led to low pitch attitude and insufficient forward velocity reduction. TP3 achieved good speed control but overcompensated following a ballooning effect, disrupting vertical speed control. TP4 performed a sharp flare and managed forward velocity well, but used a large collective check, resulting in rapid rotor RPM decay and reduced rotor efficiency, limiting final descent control.

A common theme among the marginal cases was either insufficient or overly aggressive use of collective input, particularly in managing rotor RPM during the flare. These findings underscore the importance of timely, balanced cyclic and collective inputs, as well as rotor energy management, in achieving consistent autorotation touchdown performance. While different pilot backgrounds and styles influenced technique, the most effective strategies combined early energy conversion, rotor RPM preservation, and precise control during the flare recovery phase.

From the analysis it appears that pilots trained in Royal Navy are cautious about the RPM control in the flare phase and applies the notional "step input" in the collective X_C when compared with the pilots trained by Royal Air Force.

6.2. Piloting techniques from in flight test points

The data collected in flight data demonstrate generally lower descent rates and tighter control near the ground, reflecting both pilot caution and operational realism.

The four piloting techniques observed during the OH-58 flight test points illustrate the variability in how various pilots manage flare timing, pitch attitude, and rotor energy. Techniques 1 and 2 demonstrate more traditional, structured approaches with gradual cyclic inputs and modest collective use, prioritizing pitch control and RPM preservation. In contrast, Techniques 3 and 4 rely on extended flare durations and more substantial collective inputs—particularly during pitch-down—to manage descent and maintain rotor speed. Notably, Technique 4 achieved the greatest forward speed reduction, highlighting the effectiveness of longer flare phases in dissipating kinetic energy. However, this comes with increased demand on timing and collective coordination. The variation in collective step input—ranging from 15% to 40%—also underscores different strategies for rotor RPM control, with larger inputs offering better speed management but potentially accelerating rotor RPM decay. Overall, the real flight data confirm that multiple flare strategies can achieve acceptable outcomes, though the most effective landings depend on a well-balanced use of pitch attitude, forward speed decay, and timely collective application.

The Bell 206 autorotation manoeuvres reveal two distinct yet effective piloting strategies for managing the flare and touchdown phases. Both runs initiated the flare at relatively low altitudes (88 ft and 120 ft) and achieved similar reductions in pitch attitude and descent rate, yet their control inputs in X_C varied. The pilot in Run 6 employed a more gradual and energy-managed flare, combining early collective input with a smoother pitch response to maintain rotor RPM and minimize descent rate. In contrast, the pilot in Run 7 relied on a delayed but rapid collective build-up during the final moments before touchdown, compensating for a slower pitch response earlier in the flare. Despite their differences, both approaches-maintained rotor RPM within acceptable bounds and produced successful landings. These results suggest that while optimal flare execution may vary, precise timing and coordination of cyclic and collective controls remain critical for autorotation success.

7. CONCLUSIONS

This study has presented a comparative evaluation of pilot techniques during autorotation manoeuvres across simulated and real flight environments. By analysing data from the FGR simulation model and in-flight tests using Bell OH-58 and Bell 206 helicopters, key similarities and differences in control strategies were identified—particularly during the flare phase.

Identified similarities across simulated and flight tests are as follows:

- All pilots followed a broadly consistent structure of the autorotation manoeuvre, progressing through the expected phases: entry, steady descent, flare, and touchdown.
- Similar techniques were applied by all the pilots in the first two phases (engine fail to steady state, and steady state)
- During the flare, pilots consistently used aft cyclic input to pitch the nose up and forward cyclic to level the aircraft before touchdown.
- A gradual increase in collective input near touchdown was a common strategy to cushion the descent, regardless of whether a collective "check" was used earlier.

Identified differences across simulated and flight tests are as follows:

- Flare initiation height varied more in real flights, ranging from ~88 ft to over 200 ft, while simulator pilots tended to flare between 150–220 ft.
- Cyclic input styles were more aggressive and varied in the simulator, whereas in-flight pilots tended to use smoother, more conservative inputs.
- Use of the collective "check" input (a step input to manage rotor RPM) was inconsistent in simulation and appears to be dependent on the pilot’s training/background.
- Rotor RPM trends differed: simulator pilots experienced both overspeed and under speed events due to timing of collective input, whereas in-flight pilots maintained tighter RPM control, likely due to risk awareness and aircraft limitations.

The results show that a range of techniques can lead to successful landings, provided that pilots apply timely and well-coordinated cyclic and collective inputs. Differences in flare initiation altitude, pitch angle management, and collective application significantly influenced descent rate and forward speed at touchdown. Marginal landings were typically linked to delayed or insufficient collective use or overly aggressive flare responses, highlighting the need for precise judgement during this high-workload phase. These findings underscore the critical role of pilot technique in autorotation success and suggest opportunities to refine training methods and simulator cueing to better reflect the dynamic demands of the flare and landing phases.

Author contact:

Mushfiqul Alam – mushfiqul.alam@cranfield.ac.uk

Michael Jump – mjump1@liverpool.ac.uk

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