AUTOROTATION MANEUVER ANALYSIS OF MAIN ROTOR AND AIRCRAFT FLIGHT FROM ENGINE FAILURE TO GROUND CONTACT

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Abstract

Under the framework of the US/France Memorandum of Agreement (MoA) for Cooperative Research on Helicopter Aeromechanics, ONERA and AED collaborated with the creation of a new task concerning helicopters autorotation ability in 2011. The objective of this task was to investigate the improvement of flight safety and performance of helicopters when operated in autorotation, from the engine failure detection to the final touchdown. Autorotation flight maneuvering including heading and airspeed control algorithms that could be adapted for pilot cueing or automated maneuvering to a safe landing zone and flare initiation characteristics for landing were also studied.

List of abbreviation

MoA	Memorandum of Agreement
AED	Aviation Engineering Directorate
ONERA	Office National d'Études et de Recherche Aérospatiales / French Aerospace Lab
DGA EV	Direction Générale de l'Armement Essais en Vol / French Flight Test Centre
FCS	Flight Control System
GPS	Global Positioning System
GUI	Graphical User Interface

List of symbols

DDT0	Collective position (0%-100%)
RoD / VZ	Rate of descent
IAS	Indicated Airspeed
$TQ_{ENGFAIL}$	Engine Torque at engine failure
NR_{FAIL}	Rotor rpm at engine failure
LZ	Landing Zone
γ	Glide Slope angle
ϕ	Roll Angle
θ	Pitch Angle
ψ	Heading
K_{VH}	Coefficient applied on airspeed (identified from flight tests)
K_{GW}	Coefficient applied on gross weight (identified from flight tests)

1. INTRODUCTION

Since autorotation is the only means of safely landing a helicopter following engine failure(s), tail rotor loss, or transmission failure, understanding the mechanisms governing this flight condition and improving safety during this particular maneuver remains a substantial challenge for the helicopter community.

In the framework of the US/France Memorandum of Agreement (MoA) for Cooperative Research on Helicopter Aeromechanics, ONERA and AED shared their experience with the creation of a new task concerning helicopter autorotation ability in 2011.

The objective was to investigate potential improvement of flight safety and/or performance in autorotation from the initial engine failure to the final touchdown.

This program addressed the phases of autorotation:

- Study of the entry following an engine failure (the first 3 to 5 seconds)
- Maneuvering in stabilized autorotation (towards the landing zone)
- Study of the final touchdown (flare maneuver)

Within the three phases, France and the US studied the enabling systems and technologies (semi-assisted procedures / fully automated, etc.).

For both the two first phases, the technical approach has been similar:

- Validate and if needed, upgrade the flight mechanics models through comparisons with flight tests
- Organize and/or gather an experimental database
- Use the models to study optimized procedures or dedicated FCS or piloting aids.
- Validations on flight tests or through simulations

The third phase has been partially initiated by AED, with flare and collective pull preliminary studies.

2. FLIGHT MECHANIC CODE COMPARISONS, TUNING AND VALIDATION

2.1 Flight tests and experimental database gathering

In order to gather an experimental data base, flight tests were performed to enable the Airbus Helicopter's flight mechanics code "HOST" (Helicopter Overall Simulation Tool) validation against flight data. Since the study required extensive flight testing and experienced test pilots, the French Flight Test Centre (DGA EV) and ONERA worked in close cooperation to conduct these flight tests.

A total of 10 flights were performed, providing 143 autorotation test points performed on two Fennec helicopters (AS-550 U2). Although mainly dedicated to the analysis of the main rotor dynamics (rotor rpm drop after throttle cut, rotor rpm variations due to longitudinal inputs, etc.), they also provided data on stabilized autorotation descents and full autorotation maneuvers down to the ground.
The Flight Test Instrumentation provided all flight parameters (attitudes, rotor rpm, speeds, etc.) as well as precise helicopter location thanks to the use of a differential GPS.
These flight tests provides a broad and very specific database which enables to study the mechanisms governing the autorotation entry and stabilized phases as well as the most influential parameters.

AED has collected a database of more than 80 OH-58D and 40 UH-60M autorotation entries and landings. This database has been organized upon gross weight, pressure altitude, and maneuver. The database provides flight test data for entering autorotation through a collective reduction or throttle reduction. The database does not address lateral maneuvering from an autorotation.

2.2 Flight tests matching techniques and model validations

Instead of using the inverse simulation utility available in HOST, a specific "black box" version developed at ONERA was used. Coupled to the MATLAB® code, it allowed the development of several "auto-pilot" modes to follow user-defined flight test parameters. Based on PID feedbacks, these modes provided the possibility to follow flight test data and reproduce the maneuvers performed in flight, or to perform maneuvers defined by the user.

For flight mechanic code comparisons, some parameters were followed as recorded in flight (collective, torque, fuel flow) while others were used as target values (helicopter attitudes, airspeed, etc).
The following options are offered to select the parameters to be tracked:

- Pilot collective following / Engine Torque following (with a potential offset)
- Possibility to follow the helicopter attitudes (Roll angle, Pitch angle, heading) or to maintain initial values: Attitude following mode.
- Possibility to follow the helicopter airspeed or to maintain initial airspeed value: Airspeed following mode.
- Rotor rpm and rate of descent are free of constraint variables, results of the flight mechanic code computations.

As the effort for tuning all the parameters, especially flight mechanics parameters, would have been too long and effort, the first objective has been to validate the main rotor rpm response. Consequently, a rather limited number of model parameters have been modified during the model validation process.
Model modifications consequently to flight test comparisons can be summarized hereafter:

- The transfer matrix from pilot commands (%) to swashplate angles (deg) have been changed.
- Engine data (Free turbine nominal speed, Rotational speed, anticipator, gas generator inertia, etc)

Figure 1 shows a comparison between flight test parameters (red line) and HOST results (blue and green lines) for the AS550-U2 autorotation. During this test point, autorotation is initiated by a fuel flow decrease (i.e. throttle cut) at 1s, leading the reduction of the engine torque. This procedure was generally used for autorotation entries. In order to study some stabilized autorotation phase, a collective drop desynchronizing the rotor and the engine was also applied.
The collective variations used as inputs in HOST are the same as in flight, as well as engine torque variations.
So, in spite of potential offsets with the experimental data, the simulation was driven by:

- cyclic and pedals commands from autopilot modes
- engine torque = flight data
- collective = flight data
- depending on the selected autopilot modes : attitudes or airspeed = flight data

In Figure 1, the blue curve represents the "attitude following mode" while the green dashed curve shows the "Initial IAS hold" mode.
The rotor rpm response of the model is very close to the experiment. When holding the IAS, the rotor rpm shows a slight discrepancy due to the lack of pitch dynamics.
In most cases, the "attitude following mode" was used to perform flight mechanic code comparisons. In this mode, it can be seen that the roll and pitch angles are relatively well tracked, while the heading is perfectly followed. Nevertheless, the resulting IAS given by the code is different from the experimental data.

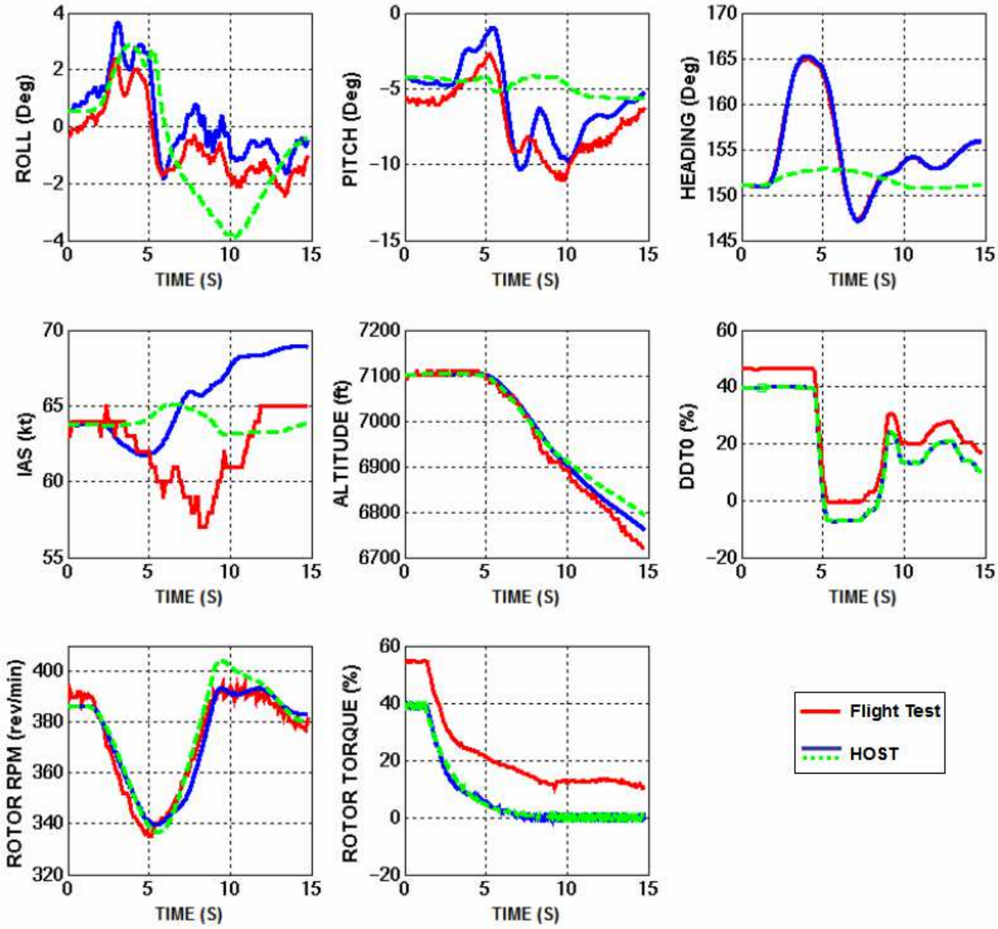

Figure 1: Flight mechanics code comparisons against flight test data

The numerous flights allowed for the model validation on a broad range of type of maneuvers. This provided the possibility to analyze the model with respect to:

- The critical time delay for pilot response
- Autorotation entries from different IAS and vertical speed (i.e. engine torque),
- IAS variations once in stabilized autorotation,
- Inputs on long / lat cyclic,
- Different stabilized rotor rpm (low and high),
- Complete autorotation maneuvers,
- Effect of turn rates on the loss of altitude.

The following Figure 2 illustrates a comparison between HOST (blue line) and flight test data (red line) for an AS550-U2. This test point corresponds to an autorotation entry and a stabilized autorotation at a high rotor rpm of 420rev/min.

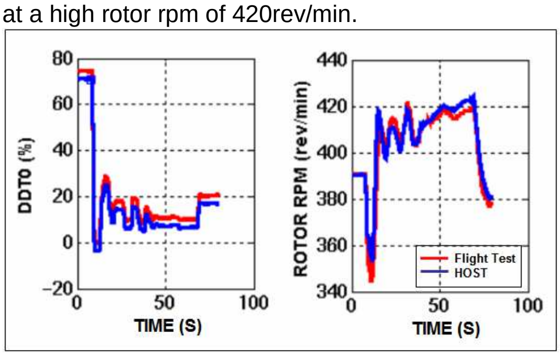

Figure 2: Stabilized autorotation at high rotor rpm

Still using the same collective variations of the flight, it can be seen that the model correctly predicts the rotor rpm variations.

Figure 3 represents a comparison between HOST (blue line) and flight test data (red line) during an autorotation entry and a stabilized autorotation with a right turn at 20° bank angle.
The "attitude following mode" is used to fly the maneuver and to follow pitch angle, roll angle and heading. The rate of descent, altitude, and rotor rpm being results of the flight mechanics code, a good agreement between the code and the test data can be seen on these parameters. Nevertheless, the IAS shows a discrepancy due to the offset on the pitch attitude.

Figure 4 shows a similar comparison between flight test data and simulation data. However, Figure 4 compares AED's FLIGHTLAB® model for the UH-60M autorotation. In the sample, the clutch on the Blackhawk was engaged at 5.5 seconds, leading to a piloted collective drop to maintain rotor speed. The model does struggle tracking body parameters in the first second, but correlates well after the initial engine failure.

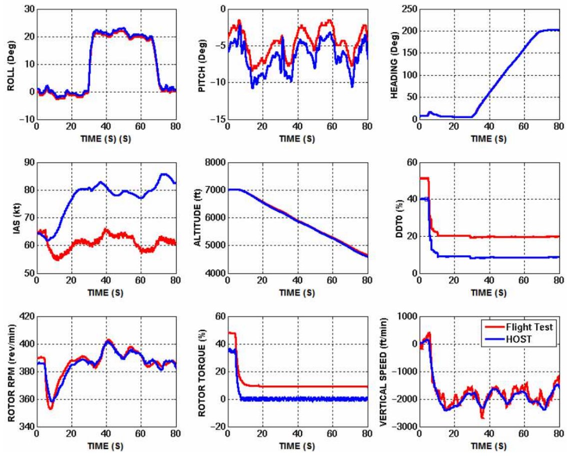

Figure 3: Stabilized autorotation at high rotor rpm

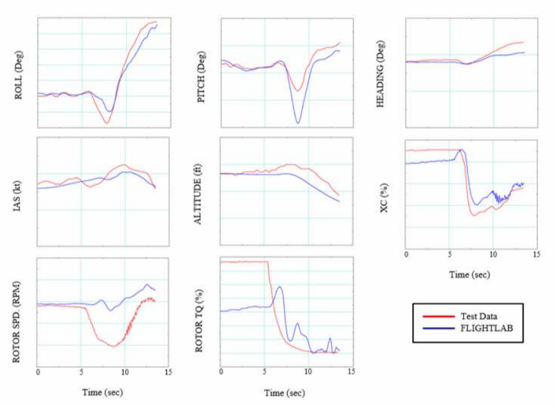

Figure 4: Stabilized autorotation for UH-60M

For the landing criteria and maneuver algorithms discussed in the coming sections, the model inputs and targets were implemented into AED developed software to replicate pilot inputs.

Following an engine failure, the pilot will need some time to recover the aircraft rotor speed and position for the opportunity to conduct a safe landing. Figure 5 is one consideration the pilot must address. The plot depicts main rotor speed in steady-descent, indicated forward airspeed, and the descent rate. Rotor speed and indicated airspeed are the independent variables. The data has been computed through FLIGHTLAB®. It appears that an 85% rotor speed is ideal for reducing the rate of descent mostly because it is achieved with a collective input. However, later sections of the paper will show that the 15% of rotor speed lost will greatly diminish the aircrafts ability to cushion a landing.

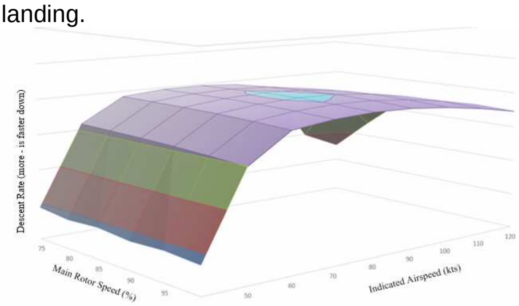

Figure 5: Descent Rate for Steady Autorotation

Therefore, the figure seems to support that a forward airspeed of 70 kts or higher at 100% rotor speed is ideal for a pilot to maneuver to a landing zone.

2.3 Simulation tools

Following validation of the model, simulation tools were developed to facilitate comparison with flight test data, to perform parametric studies or to study optimized procedures and potential piloting aids for each phase of the autorotation.
Used in off-line computations, ONERA developed simulation tools offering a large range of possibilities to control and manage different maneuvers, as well as autorotation flight.

The available options proposed to the user are:
- Command limits (ON/OFF)
- Choice of different auto-pilot modes :
    - P.Q.R. (angular speeds, i.e. SAS)
    - U V ψ (horizontal speeds control + heading)
    - ϕ θ ψ (helicopter attitudes, i.e. ATT mode)
    - U V ψ H (horizontal speeds control + heading + altitude hold)
    - U V W R (horizontal speeds control + RoD + yaw rate)
    - OFF (No autopilot)
- Axis disengagement
- Predefined actions / “piloted” simulation :
    - Predefined actions:
        - Rotor rpm trim (settling rotor rpm to a given value)
        - Engine power trim (settling engine power to a given value)
        - Actions on the collective: Number, Amplitude, time, type (step, ramp, “optimized shape”)
        - Actuator dynamics (ON/OFF)
        - Wind gusts (amplitude, heading, time)
        - Engine failure (time)
        - Forward speed variations
- “piloted” simulation : through a specific GUI (Figure 6)
    - Rotor rpm trims: buttons to settle rotor rpm to a high value (420rev/min), a low value (330rev/min) or to hold the rotor rpm at its current value.
    - Airspeed trims : buttons to settle the IAS at Vy speed (65 knots) or at Vy+25knots
    - "Sliders" to directly pilot the collective, IAS or turn rate
    - Level of collective is shown (from 0 to 100%)

  The rotor rpm indicator has been reproduced.

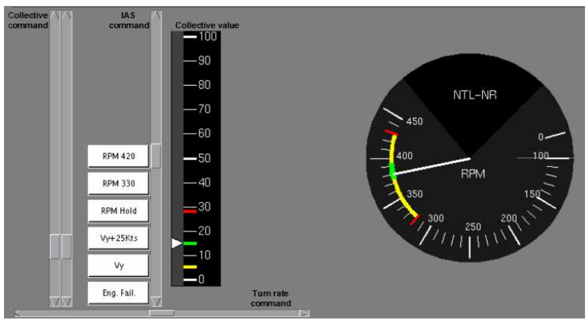

Figure 6: MATLAB® GUI for "piloted" off-line simulations

AED has developed software to attempt to replicate a pilot's cyclic, collective, and pedal motion in a cockpit based upon a achieving a flight criteria. This software has been labeled the VirtualPilot. The VirtualPilot uses the error in aircraft state, whether it is airspeed, roll angle, rotor speed, sideslip, etc., and calculates a change in cyclic, collective, or pedal position. The position is then input into the dynamic aircraft model and incremented one time-step.

3. AUTOROTATION ENTRY

ONERA mainly focused on the autorotation entry and the capability of the pilot to recover the nominal rotor rpm. In a second step, new strategies were studied to control the trajectory toward a landing zone and to develop piloting aids.

In an autorotation, rotor rpm is the most critical parameter. It provides the lift required to stabilize an acceptable rate of descent and the energy necessary to cushion the landing. Collective should be moved to the full down position to maintain rotor rpm immediately following a loss of power. The analysis of the flight tests allowed to estimate the maximum time delay offered to the pilot to react and to decrease the collective before a too strong deceleration of the rotor. Starting from the equation of the rotor speed decay following power failure:

$$\Omega(t) = \frac{1}{\left(1+\left(\frac{t}{\tau}\right)\right)} \times \Omega_0 \quad \text{with} \quad \tau = \frac{I \times \Omega_0}{Q_0} \qquad (1)$$

where

Ω_0 = Rotor RPM at the engine failure

Q_0 = Torque at the engine failure

Figure 7 shows the variation of the rotor rpm following an engine power reduction occurring at 1s (red line).

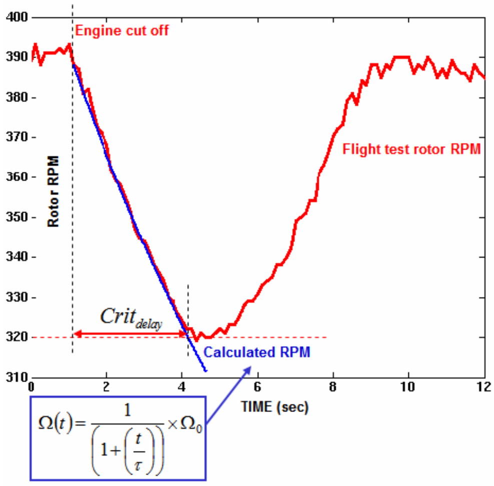

Figure 7: Estimation of rotor rpm decrease

During this test, the pilot let the rotor rpm decrease down to the minimal authorized speed. The blue curve represents the calculated rotor rpm provided by equation (1), showing a very good agreement with flight data.

On the Fennec helicopter (AS550), the minimal authorized rotor rpm is Ω_{min} = 320 rev/min, the nominal being Ω_0 = 390 rev/min. The critical time delay, which is the time needed by the rotor to decrease from the nominal to the minimum authorized speed, can be written as:

$$Crit_{delay} = \left(1 - \frac{\Omega_{MIN}}{\Omega_0}\right)\left(\frac{\tau \times \Omega_0}{\Omega_{MIN}}\right) = \left(\frac{\Omega_0 - \Omega_{MIN}}{\Omega_{MIN}}\right)\left(\frac{I \times \Omega_0}{Q_0}\right)$$

with

$I = \text{inertia used} = 2250\,\text{Kg.m}^2$

Or:

$$Crit_{delay}(t) = \left(\frac{390-320}{320}\right)\left(\frac{2250 \times 100 \times 390 \times 390 \times \left(\pi/30\right)^2}{TQengfail(\%) \times 496000}\right)$$

where

496000 = Reference power

TQengfail = Engine Torque at engine failure

It is then possible to plot the critical time delay as a function of the engine torque (Figure 8):

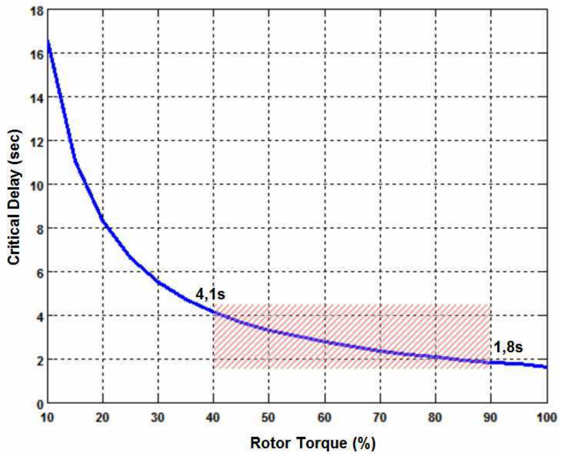

Figure 8: Critical time delay as function of engine torque

The critical delay varies between 1,65 s for 100% of torque and 16,55 s for 10% of torque. The red area corresponds to regular torque values in flight. Corresponding minimum and maximum critical time delay values are 1,8s and 4,1s, highlighting the need for a very quick reaction of the pilot after an engine failure and the likely benefit of the use of an automatic system recognizing the engine failure and managing the collective decrease.

Based on the analysis of the flight test data, the variation of the collective level needed for stabilizing the rotor rpm has been identified. First an estimation of the rate of descent in stabilized autorotation ($VZ_{autorotation}$) is performed, based on the rotor rpm (NR_{FAIL}), gross weight (GW) and engine torque ($TQ_{ENGFAIL}$) at the engine cutoff time:

$$VZ_{autorotation} = \frac{\left(NR_{FAIL} \times TQ_{ENGFAIL} \times 496000\right)}{GW \times 390 \times 100}$$

Then the collective variation (from the current collective position) is computed as a function of the IAS and gross weight (GW):

$\Delta DT0 = K_{VH}(IAS) \times VZ_{autorotation} + K_{GW}(GW, IAS)$

In addition, the collective level corresponding to high rotor rpm value (420rev/min) and low rotor rpm value (330 rev/min) are estimated:
DT0420 = f(IAS, GW)
DT0330 = f(IAS, GW)

The relations between these parameters have been identified from the analysis of different flight tests, as shown in the following figure (Figure 9):

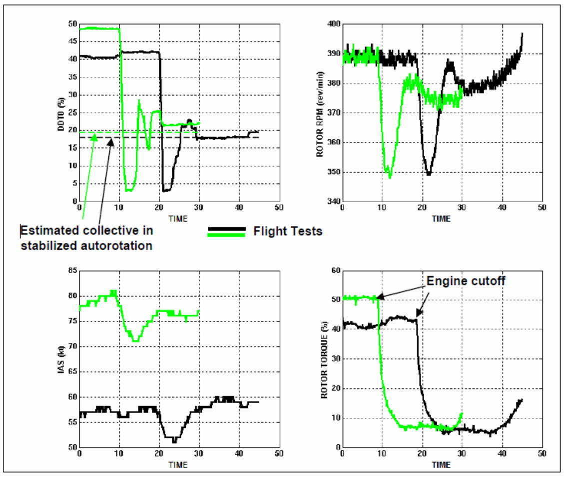

Figure 9: Use of flight test data to identify collective position values in autorotation

Solid lines represent parameters on two different flights. In both cases, pilots reacted (decreased the collective) at the same time of the engine cutoff. The only difference was the initial airspeed (which was maintained during the test), around 57 knots for black lines and 77 knots for green lines. It can be seen that once the collective is decreased, the rotor rpm increases, requiring an increase of the collective to avoid possible rotor overspeed. Then the pilot has to find the correct level of collective in order to hold the autorotational rotor speed. This is the case in the first example (black lines) while the stabilized rotor rpm is a bit lower than 390 rev/min in the second test, which could be explained by a slight too high level of collective.
As dashed lines show the estimated collective using previous equations, it can be seen that the estimated and the real collective values are the same in the first case, but the piloted collective is higher than the estimated one in the second case, contributing to a lower rotor rpm as mentioned before.

Similar flight tests were used to identify the required collective level corresponding to low and high rotor rpm (see Figure 2).

4. MANEUVERING IN STABILIZED AUTOROTATION

Based on these prior results, the knowledge of the required collective in stabilized autorotation provides a much quicker response than simple "PID" controllers. It can be used for generating an optimal collective command and constitutes the base of different piloting aids concepts which were developed by ONERA, such as a visual indicator or auto-pilot modes.

The expected benefits of estimating the required collective level are as follows:
- The reduction of the workload required to achieve and maintain the desired rotor rpm
- The use of the rotor rpm to control the glide slope

The following figure (Figure 10) shows the results of a HOST simulation which can be divided into four sequences:
1. At 1s, an engine failure occurs and the collective is immediately decreased to the level (green mark) corresponding to the autorotational rotor speed (390rev/min). After the transient phase, the rotor rpm re-increase to 390rev/min.
2. At 15s, the collective is decreased to the value corresponding to a high rotor speed of around 420rev/min.
3. At 30s, the collective is increased to the value corresponding to a low rotor speed of 330rev/min.
4. At 45s, the collective is decreased to the value corresponding to the autorotational rotor speed (390rev/min).

IAS is maintained almost constant during the maneuver thanks to the "Initial IAS hold" auto-pilot mode.

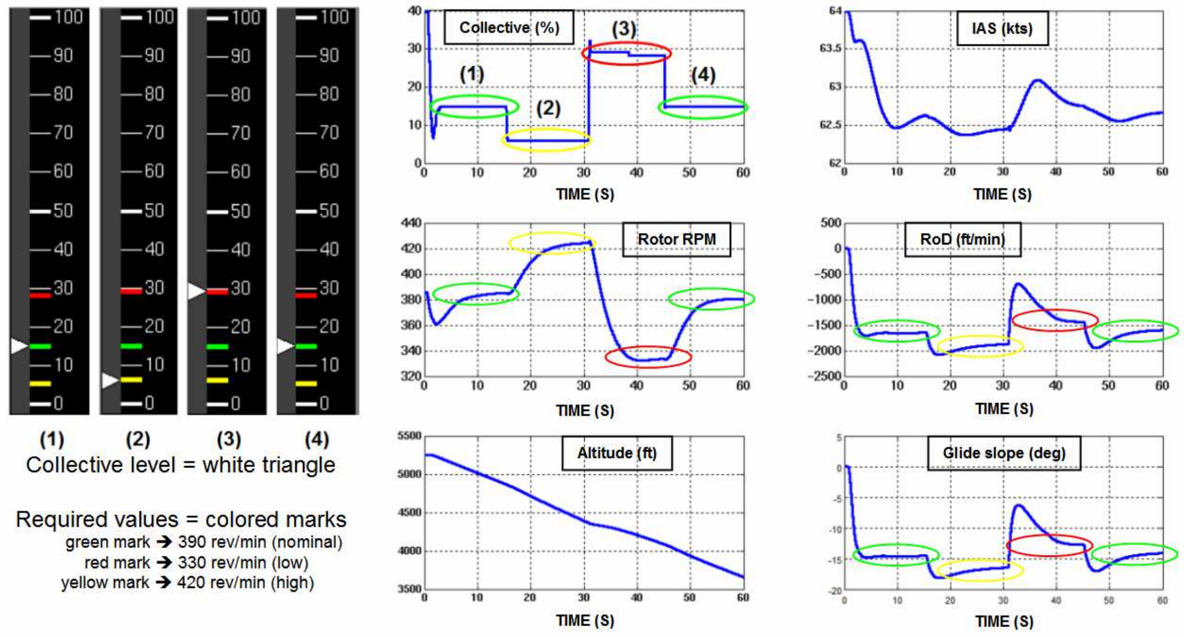

Figure 102: Use of the rotor rpm to control the rate of descent

In order to control the collective level, a graphical interface showing the current collective value and the required value was developed in MATLAB® (left graph on Figure 10).

It can be seen that, while holding the IAS to a nearly constant value of 62,5 knots, the variation of rotor rpm enables the control of the rate of descent (RoD) and thus, the glide slope. The stabilized RoD varies from 1650ft/min (-14,6°) to 1850 ft/min (-16.3°) and 1425 ft/min (-12.7°). The maximum range of collective variation leads to a maximum of 425 ft/min of the vertical speed, or 3.6° of glide slope.
Generally, pilots manage the rate of descent essentially through the airspeed, keeping a constant rotor rpm as far as possible. Vy speed (65kts for the AS550) providing the minimum rate of descent, Vy + 20/25 kts the best range.

Nevertheless, depending on the location of the landing zone, it is sometimes necessary to increase the rate of descent (if the LZ is closed) by reducing the airspeed or performing turns.

Sometimes, in order to reduce the glide slope, a low rotor rpm can also be applied as shown in Figure 11, where the glide slope is plotted as a function of forward speed and rotor rpm. Comparable to Figure 5, the surface corresponds to flight mechanic code results while dots have been identified from stabilized flight test points.

Enabling the pilot to precisely control the rotor rpm could increase the range of reachable glide slope and thus, the range of reachable landing zones.

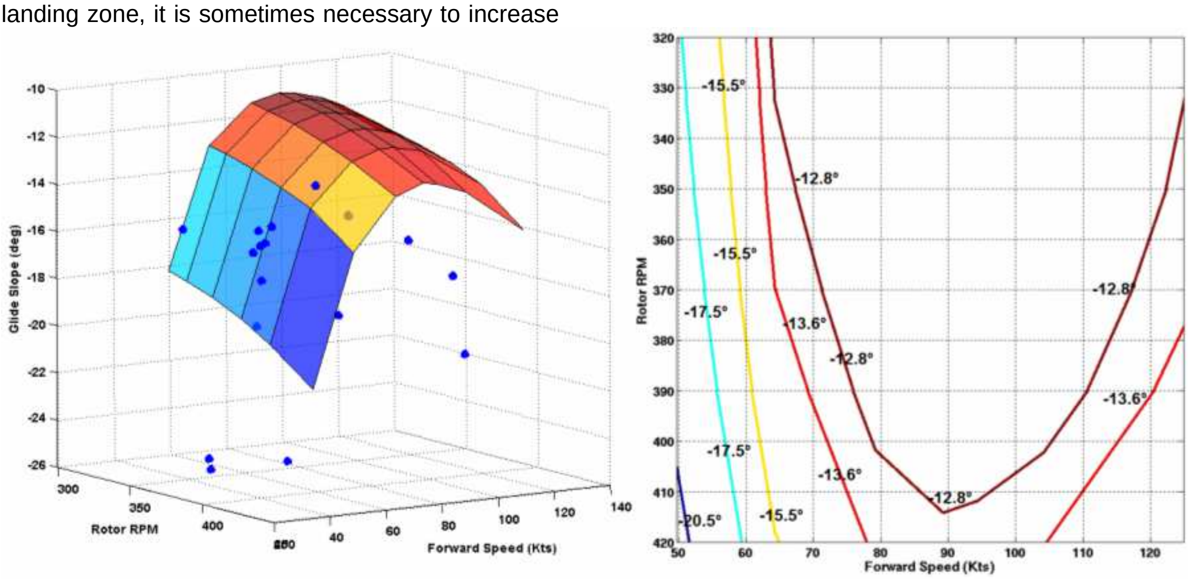

Figure 11: Relation between RoD, forward speed and rotor rpm

In order to validate in flight the algorithms providing the level of collective to reach and maintain stabilized rotor rpm, a visual indicator has been developed in close cooperation with DGA EV and has been integrated into a Fennec deck, displayed on a MFD.

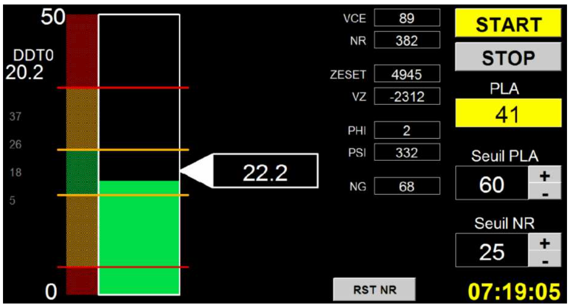

Figure 12: Visual indicator display

Figure 12 represents the exact page displayed onboard. The logic is based on the commonly used green (required), orange (alert) and red (danger) areas to cue the pilot towards the good level of collective.
The purpose is to show the level of collective required to reach and stabilize the rotor rpm at its autorotational speed. This value is given in the white mark in the middle (here 22.2%). The central column (green here) is the current level of collective applied by the pilot, the exact value being shown on the left upper part by DDT0 (here 20.2%). As following a numerical value would have been difficult in flight, a first threshold is shown around this target and corresponding to rotor rpm of 397.5 and 375 rev/min (25% of margin). Positioned in this area, the central column becomes green (as it is on the figure).
Upper and lower limits in terms of rotor rpm (i.e. in terms of collective level) are represented by the red lines. Positioned in these areas, the central column becomes red while it becomes orange between.

A dedicated flight test was performed to evaluate this visual indicator. The following figure (Figure 13) represents the collective (DDT0), rotor rpm and roll angle during one of the test points.

The throttle cut occurring at 13s, the pilot immediately decreased the collective directly down to the required value (plotted in green dashed line). The rotor rpm is then stabilized closed to its nominal value at 34s, without any other pilot action on the collective. Then in order to estimate the impact of attitude changes, the pilot performed a left turn at 20° bank angle while keeping the same level of collective. The rotor rpm variation is about ± 10rev/min.

The pilot feedbacks were pretty good. The targeted collective value was correct, stabilizing the rotor rpm to its nominal speed and leading to a strong reduction of the workload which is a very good thing in such a situation.

Nevertheless, directly reducing the collective on the required value slowed down the rotor speed re-increase. Pilots should first move the collective to the full down position and then, pull up to the required position.

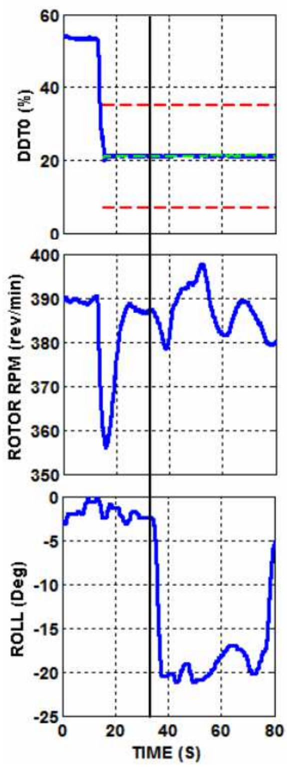

Figure 13: In flight evaluation of the visual indicator

Moreover, the rotor speed is also impacted by longitudinal cyclic inputs and these dynamic effects are not well-captured because the relations between rotor rpm, IAS and level of collective were identified from steady test cases.
While given satisfactory results, this interface was essentially used for algorithm and concept evaluation. The use of the visual channel was the only way to perform this evaluation, but it is clearly not adapted to autorotation flights where the pilots have to look outside. Based on this approach and the ability to estimate various level of required collective level, some developments have been undertaken to investigate the benefits of using haptic feedbacks to cue the pilot.

In addition, preliminary developments around other visual aids were conducted. Some of these are summarized on Figure 14.

Using a numerical terrain database showing the helicopter position, a green circle provides the ground area that the helicopter can reach at the current conditions (in terms of glide slope). Predetermined landing zones are plotted in green when still reachable or red when too far from the helicopter. For a desired LZ, selected by the pilot, required rotor rpm (and thus, required collective level) are presented.

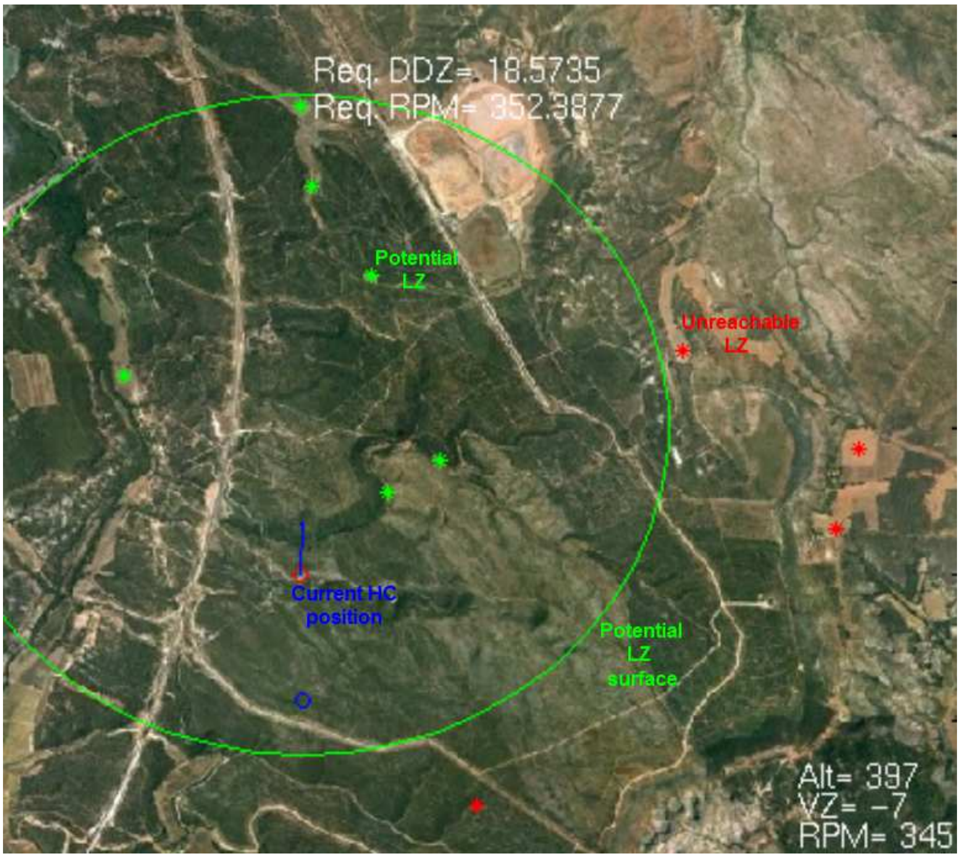

Figure 14: First developments of visual aids

Some flight test points were dedicated to the evaluation of the loss of altitude due to a turn. Figure 15 shows an example of flight test data corresponding to right turns at constant bank angle of 20° and constant airspeed. The blue line corresponds to a 90° right turn while the red line is a 190° right turn.

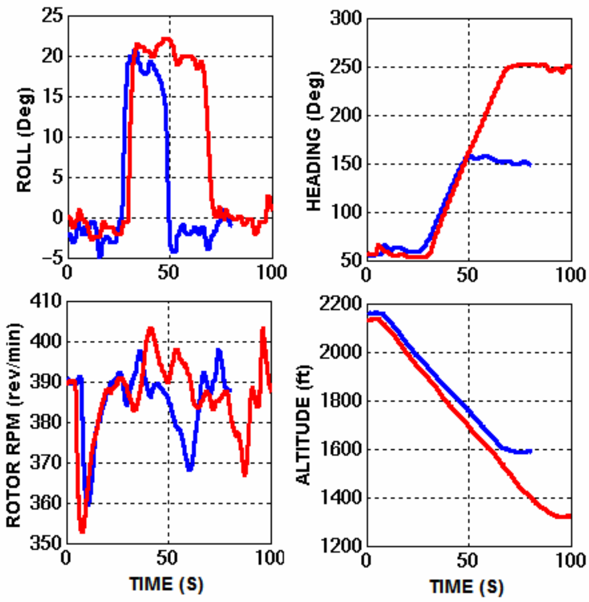

Figure 15: Evaluation of the loss of altitude in turns

The losses of altitude are respectively -575ft and -815ft. That's why, as the loss of altitude is higher when performing a large turn, the green circle (Figure 14) is not centered on the helicopter because trying to reaching a LZ behind the helicopter would require a higher altitude.

Developed and tested through off-line simulation, these types of visual aids require a deeper study in order to investigate their interest in such situations as well as the most adapted presentation channel (MFD, Helmet, HUD, Landing Zone designation, etc.). Displayed on an onboard MFD, this kind of visual aid would not be adapted. But it could be efficient if used on a helmet or projected on the windshield.

AED focused on the development of automatic systems to track the required heading and descent rate to achieve a safe landing site. The application can most effectively be applied to unmanned rotorcraft, but also has ability to assist pilots in the cockpit. Main rotor speed, bank angles with the associated descent rate, and forward airspeed control are the primary focus of the system.

For steady-descent flight in autorotation, the rotorcraft will not necessarily have a fully recovered rotor speed. The primary concern is how the rotorcraft will respond to pilot controls with 100% rotor speed or a diminished speed. Figure 16 shows the aircraft response to a lateral cyclic stick input into the system at both 100% and 85% rotor speed. For the cases described, a moderate gross weight for the Blackhawk was used. The aircraft response to a roll command is not affected by a lower rotor speed. However, if a higher gross weight were applied, the user would have to account for the possibility of blade stall when rolling. For moderate gross weight, a pilot or algorithm will not have to wait for rotor speed to recover before beginning maneuvers to track a landing position.

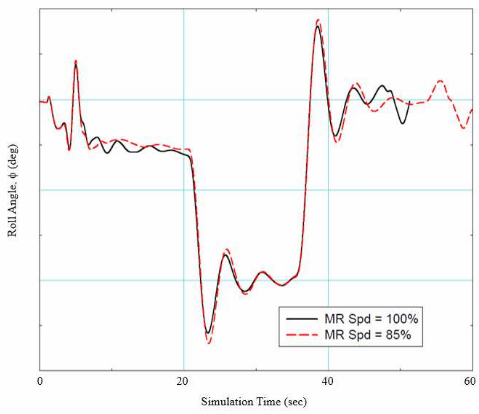

Figure 16: Roll Maneuver Sensitivity

Once determined that rotor speed (as long as it's still manageable) does not significantly affect the ability of the rotorcraft to maneuver, the aircraft is free to track state targets such as bank or pitch angle. Figure 17 shows the ability of a rotorcraft using a virtual pilot to track a commanded angle when required to do so.

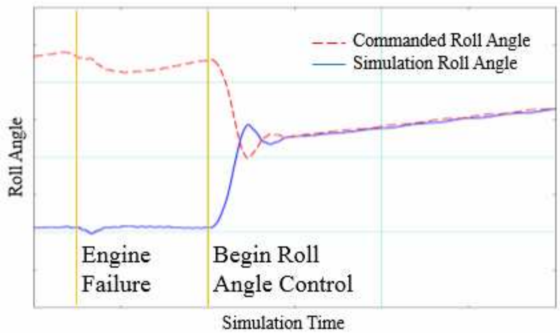

Figure 17: Roll Angle Tracking Sensitivity

Being able to achieve specific targets using pilot control allows the aircraft to be maneuvered towards a safe landing zone and to approach the criteria (airspeed, rotor speed, etc) to initiate a flare, cushion the aircraft, and safely land on the surface.

An algorithm was developed to record the aircraft's current and target position, fly a maneuver to achieve the target, and determine through glide slope angles if the target is obtainable. Such an algorithm would be beneficial not only for piloted aircraft, but also autonomous aircraft which do not rely on user input.

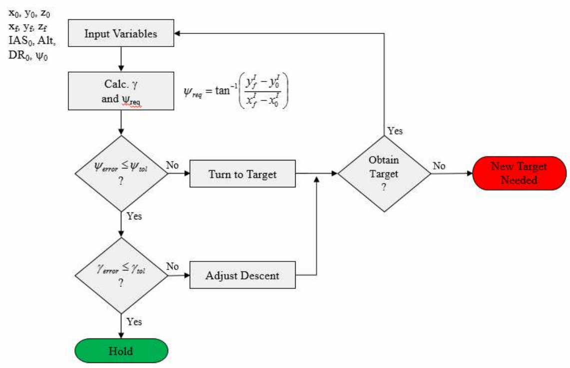

Figure 18a: Header Algorithm for Target Tracking

The algorithm is shown in Figures 18a-18c. Figure 18a is the header, while Figures 18b and 18c are subfunctions to determine targets to be inputted to the VirtualPilot.

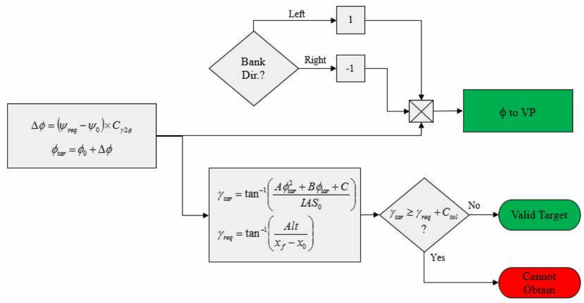

Figure 18b: Turn to Target Algorithm

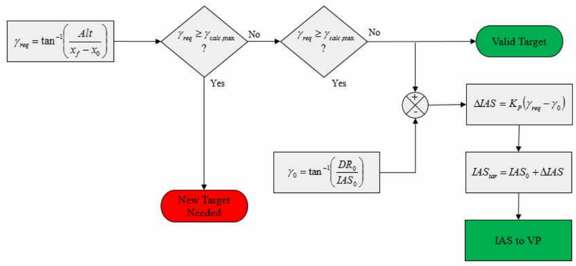

Figure 18c: Adjust Descent Rate Algorithm

The algorithm is broken into 2 main components; heading and descent. The heading phase first determines the required heading from the inertial target position and the inertial rotorcraft position. The error in heading is calculated and used to determine a bank angle to turn the rotorcraft to the target. Figure 19 shows the bank angle of the aircraft and the commanded target angle of the aircraft determined by the heading algorithm. The algorithm tracking was not initiated until an engine failure occurred, which explains the separation in the first few seconds. At its current maturity level, the algorithm must be told when an engine failure has occurred. Also, logic was added to the system to constrain the bank angle within a +/- 20 degree range.

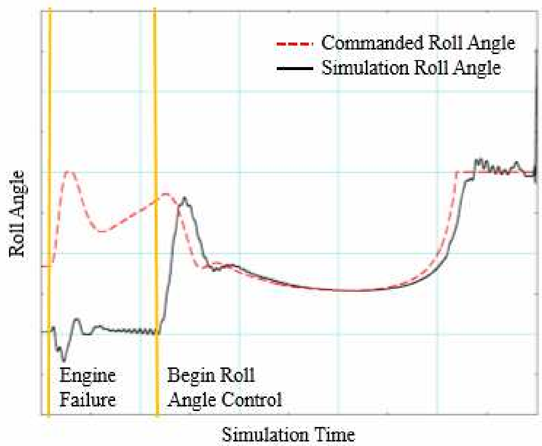

Figure 19: Commanded Roll Angle Tracking

The descent phase of the algorithm uses the glide slope angle to determine if the aircraft is going to overshoot or undershoot the target. The glide slope angle required to make contact with the target uses the difference in the xposition with the target and the altitude difference. The current glide slope angle of the rotorcraft uses the measured descent rate and indicated airspeed. The difference in glide slope is converted to a change in indicated airspeed in order to adjust the glide slope angle. The slower the speed, the greater the angle. The faster the forward speed, the smaller the angle. Figure 20 shows the indicated airspeed of the aircraft compared to the targeted airspeed found by the algorithm. The spike at the end was the aircraft passing the targeted area as it initiated its landing procedures.

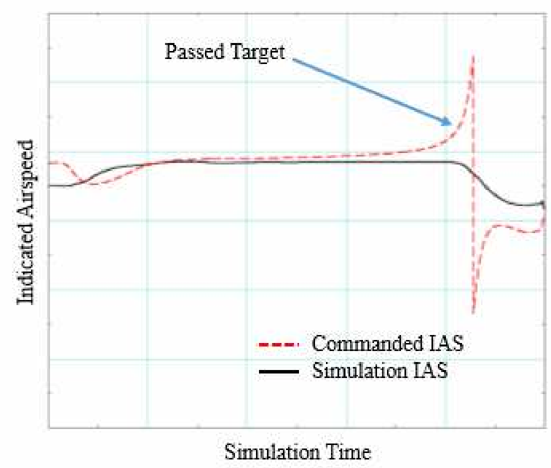

Figure 20: IAS Tracking for Glide Slope Calculation

Figure 21 and Figure 22 represent the analysis for determining whether the target is achievable. Figure 21 is the result of previous studies that associated a descent rate with the UH-60M based upon the forward airspeed of the aircraft in autorotation. The data was curve fit and used to determine the descent rate at any forward airspeed. Figure 22 sets the limits that the glide slope is to maintain in order to maintain control of the aircraft and still perform a proper landing in autorotation. The limits use the curve fit for 50 kts and 100 kts. The solid line is the required glide slope to reach the target. Because the aircraft indicated airspeed is to remain between 50 and 100 kts, if the required glide slope goes above or below the region, the aircraft will overshoot or undershoot the target area.

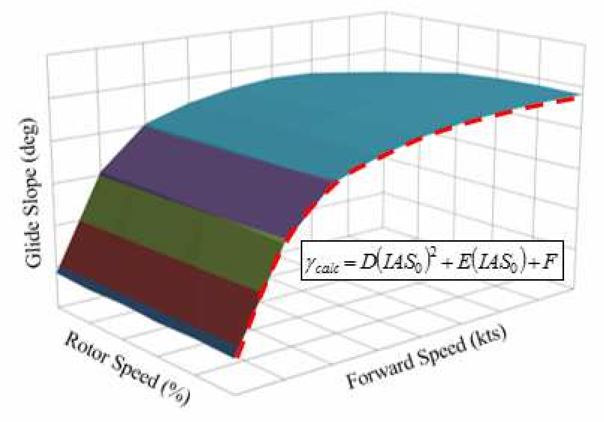

Figure 21: IAS used for Calculating Glide Slope

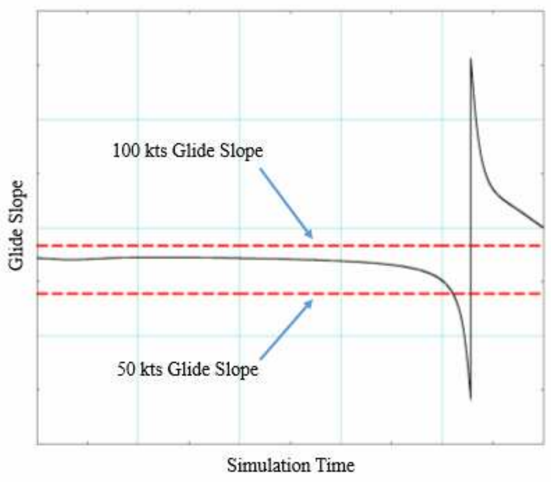

Figure 22: Glide Slope Boundary for Max./Min. IAS

Figure 23 is the final ground plot of a target tracking algorithm for an aircraft in autorotation. The first few moments are used to kill the engine and enter a steady autorotation. The aircraft shows to be within a reasonable margin of error to intercepting the target. There is still some tuning of the algorithm required. As is, a pilot in the loop should be able to recognize the fine motions to hit the target area, however, an autonomous aircraft landing will still need some tuning.

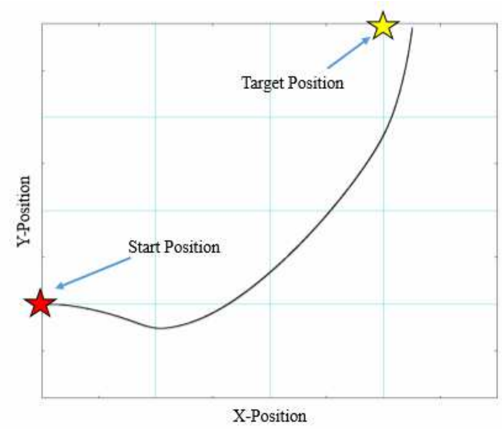

Figure 23: Target Tracking Example (Plan-View)

5. PARAMETRIC STUDIES FOR FLARE MANEUVER

The simulated landing of an aircraft in autorotation consists of two basic maneuvers. The first being a flare, a pitch-up maneuver which will slow the ground speed of the aircraft, begin to arrest the aircraft rate of descent, and cause a surge in rotor speed. The second is a collective pull timed when the aircraft nose is ready to pitch down. This maneuver uses the kinetic energy within the rotor to slow the descent rate to an acceptable ground contact speed. Determining an appropriate flare angle and collective pull is essential for creating an autorotation flight path from engine failure to flare initiation.

From Figure 24, 5 and 10 degree flares are not very effective. A flare of 15 degrees or more is better at arresting the descent rate. Note that the more aggressive the flare, the longer the flare maneuver. Since this is occurring at an altitude less than 100 feet, the pilot or algorithm must be aware of the distance from the ground.

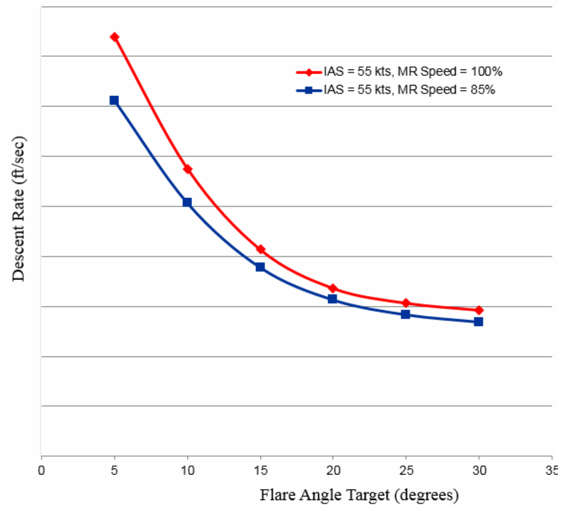

Figure 24: Flare Angle Effectiveness

Once the flare angle is achieved, the collective is pulled to control a landing to the ground. The evaluated criteria are the rotor speed at the time of the collective pull and the magnitude of the collective pull. Ground effect was accounted for when running these cases. Although a steady-descent case run with some collective input, resulting in an 85% rotor speed and a slower rate of descent than a 100% rotor speed case, Figure 25 demonstrates the effectiveness of having energy stored in a rotor for a final collective pull. The 85% case is very limited. The 100% case is very forgiving for a pilot to have a soft landing with the aircraft.

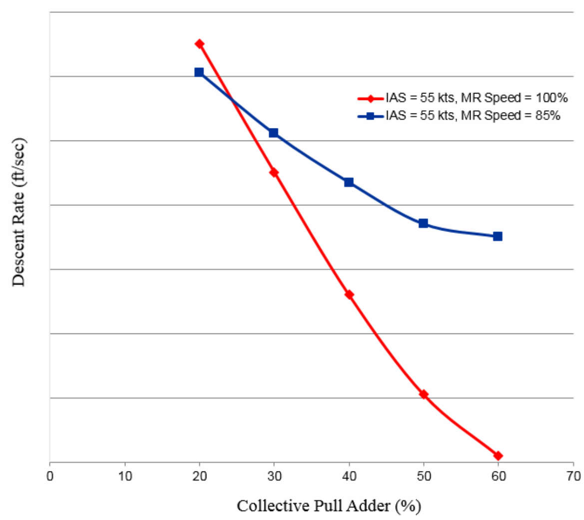

Figure 25: Collective Pull Effectiveness

Therefore, the steady-descent in autorotation should focus not only on landing position, but also time for a flare and have the energy stored within the rotor to cushion the landing.

6. CONCLUSIONS

Flight tests performed in France and existing flight tests data collected in US provided a large experimental database enabling the study of autorotation and safe landing zone tracking. The data was used to validate the dynamic simulation models; HOST for France and FLIGHTLAB® for the US.
Studies have identified entry criteria appropriate for completing a successful flare and collective pull for landing. Algorithms have been developed to maneuver an aircraft in a steady autorotation to a safe landing zone based upon controlling bank angle, forward speed, and descent rate.

The analyses also allowed for the estimation of:

- the critical time delay (maximum time delay for the pilot rotor rpm decreases below the minimum authorized value).
- the stabilized autorotation collective level (collective level needed to reach the recommended autorotation rotor rpm and avoid rotor overspeed).
- the entry criteria for a safe landing (aircraft conditions prior to and during a flare and collective pull for landing).
- the autorotation flight maneuvers (the algorithms used to determine bank angle, forward speed, and descent rate to intercept a landing site).

The simulation tools developed, based on validated flight mechanics codes, offer the possibility to reproduce or to perform simulated autorotation maneuvers in very different situations. This should allow the possibility to develop and to test piloting aid functions to help the pilots to perform this difficult maneuver in safer conditions.

7. NEXT STEPS

Autorotation is a current topic within the US/FR Rotorcraft Project Agreement. New tasks are to be developed for studying the development and implementation of algorithms produced by both France and the US onto unmanned rotorcraft. Other tasks may be developed for future studies.

ONERA intends to continue to work on piloting aid functions development and implementation on the ONERA's prototyping bench "PycsHel" for piloted evaluations (tactile cueing, visual aids, auto-pilot modes, etc.).

AED intends to complete further tuning of the autorotation maneuvering algorithm. A properly tuned command model will allow AED to investigate applications for OPV/UAV in autorotation.

8. ACKNOWLEDGMENTS

The authors would like to recognize the efforts of the late Dr. Sam Crews. As one of founders of the France-US MoA task to study autorotation, this paper would not be possible without his insight.

The authors would also like to recognize the efforts of all of the people involved in the flight test program from DGA EV and US Army.