AUTOROTATION: IS THERE A LIVE MAN'S CURVE?

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Abstract

The autorotation flight of single engine helicopters has peculiarities in terms of performance and flying qualities. This research discusses these specific characteristics from the perspective of certification processes, especially based on the FAR-27, focusing on human factors of flight safety. It describes the factors that decisively influence the workload of the pilot during an engine failure and the actions necessary to perform a safe landing in autorotation. These factors are related to natural and artificial alarms, aerodynamic imbalances, especially in the moments following the engine failure; the reaction time of the pilot and the correct lowering collective control rate. The methodology to determine the unsafe areas of the height-speed diagram, the "dead man's curve", is investigated, quantified and compared with the main international standards and validated on a flight-test campaign, performed on an aircraft (AS-350) of the Brazilian Air Force, carried out by test pilots and engineers with the Test Flight and Research Institute (IPEV). Such studies suggest a methodology to define the risk level curve instead of the dead man's curve in order to reduce the catastrophic damages resulting from inadequate interpretations of the pilots during full autorotation flight, as well as to advise the authorities involved in the process of certification of these types of helicopters.

1. INTRODUCTION

"The transition from powered flight to an autorotation flight, after a total power failure, must be analyzed under the same angle as the parachute jump, ejection or landing with engine off in a single-engine fixed wing aircraft" [1].

"Autorotation is the rotor state of operation, in which net power involved either does not exist or partially exists" [2].

"The maintenance of the main rotor *RPM* is a prerequisite for the autorotation flight. It is guaranteed by performing an energy balance involving gravitational and kinetic energy of translation, which are both converted into kinetic energy of rotor blades *RPM*" [3].

"It is a self-sustaining rotation of the rotor without the application of any shaft torque from the engine. Under these conditions, the power to drive the rotor comes from the relative airstream upward through the rotor as the helicopter descends through the air" [4].

The main civil certification standard of light and single-engine helicopters, FAR Part-27 [5], paragraph § 27.87 (a) indicates that: If there is any combination of height and forward speed (including hover) under which a safe landing cannot be made, a limiting height-speed envelope must be established. This curve is commonly known as the "dead man's curve". This diagram is built according to the qualitative assessment of flight test crews. This methodology considers a lot of height/speed combinations and, especially, the workload to perform a safe landing during an autorotation [6].

Even considering this diagram, the number of accidents involving helicopters has increased in recent decades, as seen in the NASA research [7] and ISELER, et al. [8]. When analyzing the contributing factors of these accidents, recurrently, problems related to inadequate training have been observed in the maneuvers required to perform an autorotation flight.

It is important to emphasize that even respecting the limits of the dead man's curve, the workload to perform a full autorotation, even in training, can reach unacceptable levels, depending on the type of aircraft and a number of operational and design factors.

Analyzing these accidents, particularly those related to a sudden engine failure, in general, inadequate reactions of pilots are observed, mainly related to the lack of skills to perform the autorotation flight till a safe landing.

A thorough analysis of the Aeronautical Standards, like FAR-27[5], RBAC-27[9] and CS-27[10] shows that there are many gaps and non-conservative points on their safety requirements.

These discrepancies turn to be key points during the investigation process of accidents involving helicopters. Technical documentation of aircraft certified under FAR-27 can provide non-conservative information about autorotation performance and flying qualities. That can induce pilots to think they are flying a safe flight envelope when they are not.

The FAR-27 determine that an aircraft must be able to maintain any required flight condition and make a smooth transition to any other without exceptional piloting skills, alertness, or strength, and without danger of exceeding the limit load factor under any operating condition, including sudden complete power failure.

One would ask: what does “without exceptional piloting skills” exactly mean?

There are no quantitative parameters to explain this consideration on the FAR-27, being under the interpretation of certification agencies and the common sense of the manufacturers. But, is it enough to preserve the flight safety during an autorotation?

Thus, the rationale for this research comes from the need to clarify the cause of a considerable amount of accidents that occur during the autorotative flight, even if the pilot is flying off the unsafe combinations of height and speed indicated on the dead man's curve. Furthermore, it is necessary to clarify if this methodology is adequate to guarantee the flight safety or if there are other influential parameters that are not being considered in the certification process.

Thus, it is possible to establish the following question, regarding light and single engine helicopters, certificated under FAR-27 requirements: Is there a "live man's curve"?

The objective of this paper is to identify what are the factors that affect the performance and flying qualities of an aircraft in autorotation and their associated influence in the increase of workload and exposure to risk.

This investigation hinges the presentation of the most critical factors during the autorotation flight and items of academic interest within this context. Only factors occurring at the time of engine failure and during ingress in an autorotation flight of light and single-engine helicopters are evaluated.

2. DATA ANALYSIS

“A bad ending of an autorotation is usually survivable, but a bad beginning of an autorotation is usually not.” [11]

When studying the phenomenon of autorotation, in general, there is a direct association with sudden engine failure. However, there are other reasons that make necessary to carry out such maneuver; for example, a failure of the tail rotor command, in which it is operationally recommended that the pilot shut-off the engine to cancel the torque applied to the transmission in order to avoid an uncontrolled yaw of the aircraft on final landing approach.

A similar situation occurs in case of fire in the engine compartment when, most certainly, the pilot must decide for intentional engine shutdown to mitigate the consequences of the fire.

At the exact moment of engine failure, several influencing factors determine the success of the autorotation landing procedure.

This research identifies the problems related to engine failure, aerodynamic imbalances; natural and artificial alarms; lowering collective control rate and the study of critical time, as well as their consequences on the reaction time of the pilot.

2.1. Engine Failure

The engine failure can happen due various causes: be mechanical or structural, they are due to the fuel supply system failure or lack of the fuel itself (fuel exhaustion).

In addition, the engine can be shut-off by the pilot, due operational reasons; i.e., need to cancel the torque applied to the transmission in the event of failure of the tail rotor or fire.

For each type of engine failure it is expected a sudden drop in the available torque applied to the rotor and, hence, a decrease in the main rotor *RPM*, until the pilot lowers the collective control.

The research and flight tests conducted by FERRELL, et al. [12] indicate that the drop of torque exhibits a different pattern for each type of failure, as can be observed qualitatively in Figure 1.

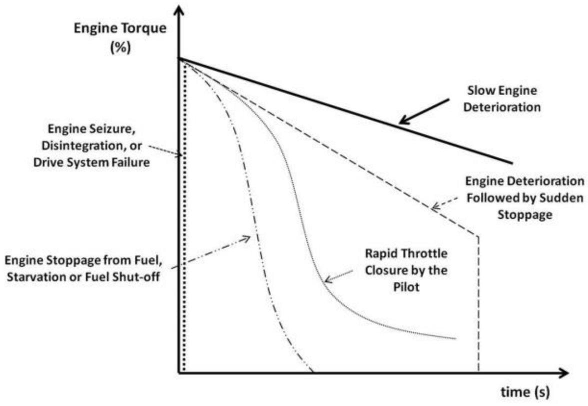


Figure 1: Engine torque reduction with type of power failure [12].

The pattern of torque drop can be (1) practically instantaneous in case of engine seizure or disintegration of the engine shaft internal mechanisms; (2) intermediate drop can happen, in the case of the engine stoppage from fuel, starvation or fuel shut-off; (3) a slow drop in case of a gradual deterioration of the engine.

The FAR-27 [5], paragraph § 27.143 (e) establishes a minimum pilot reaction time of 1s which has to be guaranteed after the engine failure for the pilot to move the flight controls. This standard establishes neither the exact time when that engine failure shall be considered, nor the type or pattern of failure with which they are associated.

Another issue to be considered is the influence of the residual power during flights of development or certification process. The AC-27 [13], paragraph § 27.79 establishes: the actual shutdown of an engine to simulate an engine failure should not be necessary if the simulated procedure ensures that the engine power is suddenly removed from driving the rotor and remains so. The normal fuel control deceleration schedule is usually satisfactory for the power removal for turbine engines but the flight or ground idle speed may have to be set lower than normal for Height-Speed testing.

According to Prouty [3], the descent rate is influenced by several factors such as speed, density-altitude and remaining torque. Thus, it is expected that in the event of a power reduction, any remaining torque condition will influence the rate of descent as well as the magnitude of the aerodynamic imbalance, altering the actual flight condition that the pilot can experience during a real autorotation.

The flight tests performed to validate these issues were carried out in the aircraft AS-350. Figure 2 shows the torque drop rate, as well as, the residual power available at the flight idle condition.

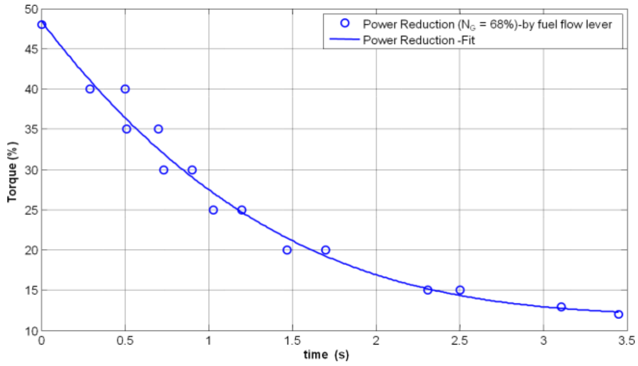


Figure 2: Residual power available.

In Figure 2, it is possible to observe that with the Engine Gas Generator Speed (*Ng*) reduced to 68% (flight idle) the remaining torque available is approximately 13%. In this condition, the rate of descent and the angular imbalances are lower than the parameters that would be found during a real engine failure situation.

Thus, it is possible to verify that the information obtained in this type of flight testing is not conservative and shall corrected to be included in the helicopter flight manual.

The correction in the helicopter descent rate is easily predicted with mathematical equations, however, the subjective evaluations of workload, especially, during the tests to determine the dead man's curve, are influenced by this remaining torque and there is no method to separate this influence .

Thus, this way, it is determined the first influential factor which is not provided in FAR-27 and making the information of flight manuals not conservative.

2.2 Aerodynamic Imbalances

When engine failure occurs, the aircraft presents a series of aerodynamic imbalances which vary depending upon the torque of the engine, flight density-altitude, CG position and forward speed [3].

The main imbalance occurs when the helicopter rotates in the same direction of the main rotor (yaw), being greatly influenced by the forward speed of the aircraft. This yaw is more pronounced in hover and low speed forward flight, decreasing progressively at higher speeds.

Under conditions of low power (torque), especially during descents, yaw due to an engine failure is virtually imperceptible to the pilot and can be confused with the effects of wind and turbulence.

Other effects that follow are the rolling caused by the yaw "*girouette* effect" [14] and the pitch down movement. These imbalances and reactions of the helicopter depend of the characteristics of static stability of the aircraft.

The major problem to be evaluated in these imbalances is the influence of necessary actions that the pilot must perform in the flight controls in order to maintain the adequate conditions to enter in autorotation.

Flight tests to validate these data were performed in open and closed-loop, with the pilot outside and inside of the flight controls, respectively, for different conditions of speed, but with the same weight and CG position. The results of the angular rates, longitudinal (*p*); lateral (*q*); yaw (*r*); in closed-loop are shown in Figure 3.

It is discussed and analyzed herein only results are that obtained in hovering flight, because they present the most critical results.

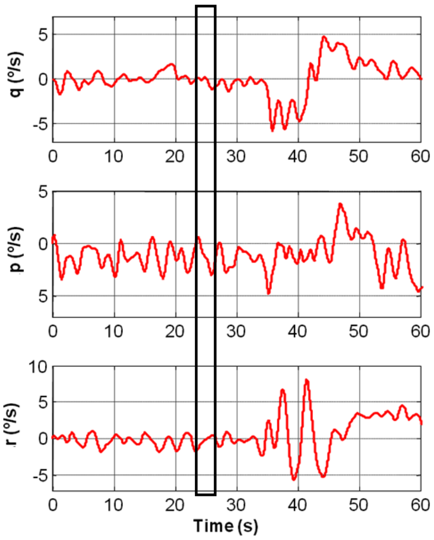


Figure 3: Aerodynamics imbalances. Closed-loop.

To analyze the workload to maintain the control of the aircraft attitude at the exact moment of the engine failure, it is considered that the test pilot shall keep the variations of angular rates, in closed-loop, below 5°/s and a Handling Qualities Rate (HQR) less than 4, as the Handling Qualities Rate Scale showed in Figure 4 [15].

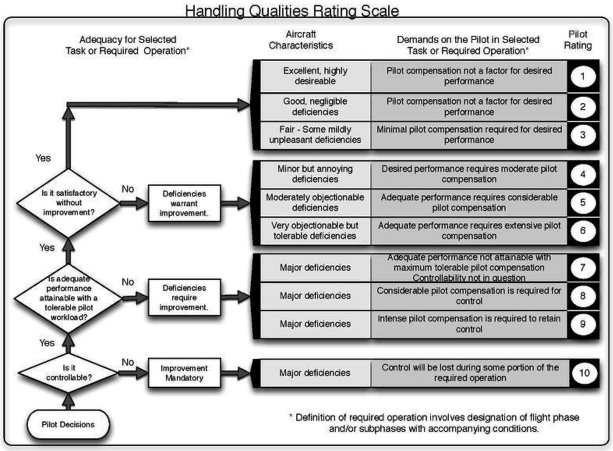


Figure 4: Handling Qualities Rate Scale [15] .

The test shows that it is possible to control the aircraft with variations of less than 3°/s on all axes, reaching the desired performance of task.

The workload to control the aircraft is low, not generating any recommendation or specific action to the pilot. Yet, when analyzing the complete data from all tests, it is observed another feature that shall be considered: When the pilot reacts immediately on the flight controls at the time of engine failure, which is not probable, the *RPM* drops to a certain value, but when he reacts only after 1s, allowing an imbalance in yaw, the main rotor *RPM* drop rate is enhanced, as can be observed in Figure 5.

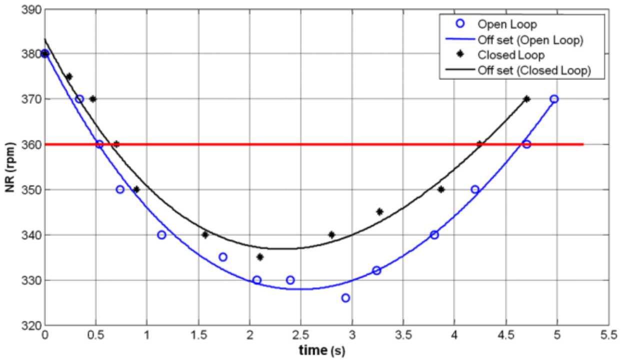


Figure 5: *RPM* droop by an aerodynamic imbalance.

The difference between the lowest rotations of these curves is about 10RPM. It corresponds to almost 15% of the maximum main rotor *RPM* drop rate permitted for this type of aircraft.

This variation is also expected and analyzed by FERRELL, et al. [12], who associates this phenomenon with: (1) the speed reduction caused by increased drag of the helicopter fuselage that is yawing and rolling; (2) the natural responses of the aircraft with positive dynamic stability and (3) the increase of the profile power due the increased angle of attack and the rotor flapped aft.

2.3 Alarms

Alarms can be divided into natural and artificial.

2.3.1 Natural Alarms

They are those that can be perceived by the pilot without any dedicated system of the aircraft [1]. These alarms come from the noise changing of the engine and transmission, as well as, from the aerodynamic imbalances in all three axes, especially in yaw.

Sound variations of helicopter engines are perceived by the pilot, usually when the engine is installed near the cockpit. In other cases, especially in an aircraft powered by turbo-shaft engines, this sound change can be masked by the noise from the main transmission. FERRELL, et al. [12] says that noise variance, even when perceived by the pilot, has a long delay to alarm the pilot in a timely manner.

The second type of natural alarm is due to the aerodynamic imbalances. Depending on the torque applied at the time of the engine failure, these imbalances can be minimal and may go unnoticed by the pilot. The smaller the torque at the time of the engine failure and the higher its forward speed is, the smaller the influence of this type of alarm.

In addition, aircraft that have enhancing stability systems such as Stability Augmentation System (SAS) may compensate these variations of attitude, annulling the natural "alarm" to the pilot.

To validate this hypothesis, it is performed a flight test of an autorotation during final approach for landing, with 65kt and rate of descent of 500ft/m. In the moments that preceded the engine failure simulation, the torque applied was 20%.

By moving the fuel flow lever to flight idle position, the difference between the initial and final torque applied to the main transmission generated imbalances almost imperceptible to the pilot, with yaw angular speed less than 2°/s, as shown in Figure 6.

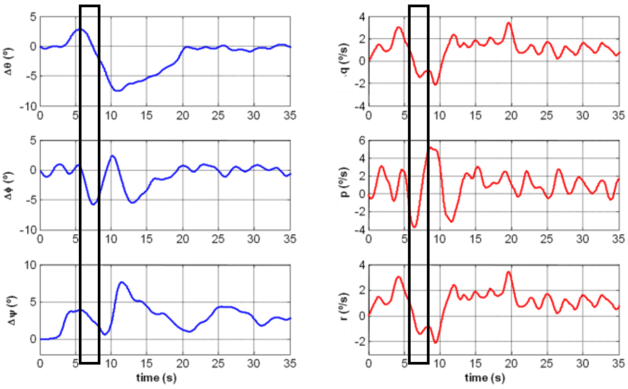


Figure 6: Angular imbalances during final approach.

This small variation in attitude, particularly in sideslip (*r*), is less pronounced than other excitations that normally occur during flight, such as small wind gusts and turbulences. This test validates the hypothesis of low efficiency of this type of alarm.

Some authors also consider variations of the flight instruments, such as a rapid decrease in indication of *Ng* and torque, as a natural warning of the engine failure. However, FERRELL, et al. [12] again indicates the inappropriateness of this type of alarm due to the inherent delays of instruments and because the pilot needs to be focused on the instruments inside the cabin at the time of the failure, to properly respond to this type of alarm.

Thus, in general, natural alarms do not provide useful information to the pilot neither in cases the engine is installed near the cockpit, nor by imbalances caused by differences in torque during descending with low power. In other flight profiles, alarms may go unnoticed or be ambiguous enough to not alarm the pilot. This shows the necessity of installing artificial alarms dedicated to this purpose.

2.3.2 Artificial Alarm

Artificial alarms are those installed in an aircraft to indicate that an engine failure occurred. They can be visual, such as warning lights or aural, like the aural warning and the voice warning.

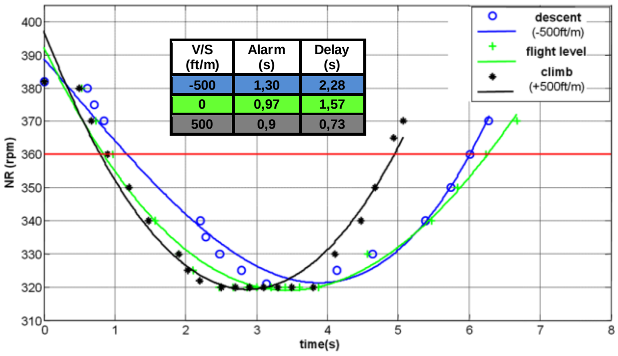
These alarms should be related to engine failure; however, some manufacturers use these alarms to indicate a main rotor *RPM* drop, which generates a delayed alarm.

The USNTPS [6] describes that artificial alarms have also vulnerabilities, such as the possibility of being canceled by the pilot, presenting false alarms and momentary indications of main rotor low speed, which may confuse the pilot during a real emergency situation.

FERRELL, et al. [12] report that the flight tests carried out during their research indicated that alarms located in the field of view of pilot associated with aural alarms are more efficient than visual alarms. That research recommends the use of both types of alarms; beyond that, their operation shall be associated with the parameter that indicates the failure of the engine as quickly as possible. Furthermore, it should be distinguishable from a normal power reduction, in order to prevent a false alarm.

The FAR-27 determine the installation of artificial alarms to indicate a main rotor *RPM* drop and not for the specific purpose to indicate an engine failure, which can considerably decrease the time that the pilot has to react during the emergency situation.

The Figure 7 presents the results of flight tests carried out in the helicopter AS-350, in three flight conditions: (1) descent (-500ft/m), (2) leveled flight and (3) climb (500ft/m), all without forward speed.



V/S (ft/m)	Alarm (s)	Delay (s)
-500	1,30	2,28
0	0,97	1,57
500	0,9	0,73

Figure 7: Main rotor *RPM* drop rate and aural alarm.

According to the AS-350 flight manual, the low *RPM* aural alarm goes off at 360RPM. During the climb flight tests, the maximum reaction time available for the pilot to act into collective control, after the power reduction, was 0.73s. In this flight condition, the alarm would sound in 0.9s. In other words, the alarm would only sound after the maximum allowed time delay to lower the collective command, proving the inadequacy of alarms related only to the main rotor RPM drop.

Thus, following the analysis of the influence of the alarms of engine failure is possible to verify the importance of having a clear, adequate, dedicated and unequivocal sign of engine failure, preferably associated with an aural warning.

2.4 Lowering Collective Control Rate

The main rotor *RPM* drop rate is directly related to the torque applied to the main transmission at the instant of engine failure.

If the pilot does not act on the flight controls, especially lowering the collective control, is expected a rapid reduction of *RPM*, tending to zero, as verified in Figure 8.

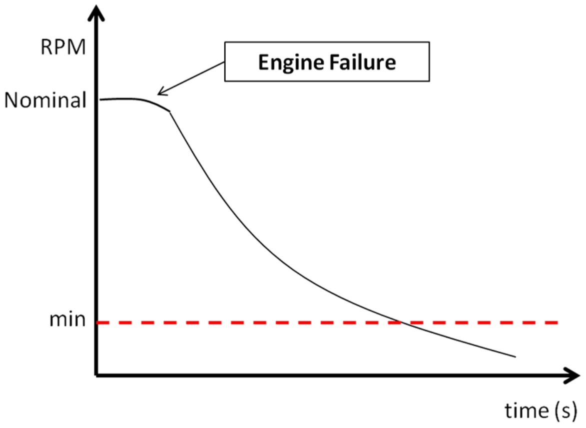


Figure 8: Main rotor *RPM* drop rate without lowering the collective control.

The validation of this theoretical prediction was performed in several test flight points, with a weight of 1.850kgf, altitude of 2.000ft , temperature of 27ºC, in hovering flight and repeated at speeds of 40, 65 and 100kt.

The flight tests related to the time involved to lower the collective control were performed on standardized time intervals (3, 2 and 1s), always starting from the same *RPM*, after the engine failure simulation, by reducing the fuel flow lever to 68% of *Ng*.

After reducing the fuel flow lever, the test pilot started to lower the collective control, triggering, concomitantly, the switch of time counter, recording the interval of time corresponding to the complete reduction of collective control and the minimum *RPM* reached. The result is shown in Figure 9.

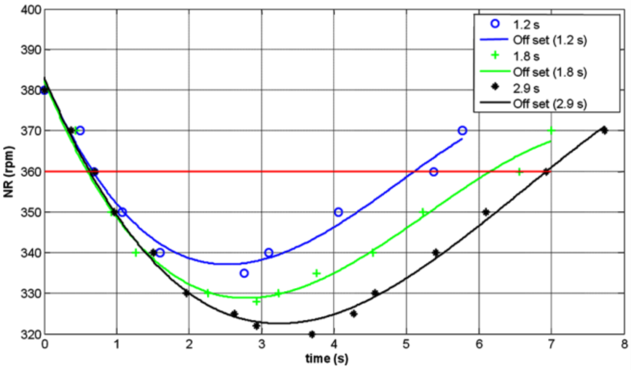


Figure 9: Main rotor *RPM* drop rate during collective lowering.

These results validate the theoretical expectations, proving that the time to lower the collective control is inversely proportional to the main rotor *RPM* drop rate. Under these test conditions, the difference between the time rate to reach the minimum *RPM* for each standard time to lower the collective control was approximately 10RPM per second.

The difference to lower the collective control from 3 to 1s represents about 28% of the maximum *RPM* loss for this type of aircraft.

2.5 Critical Time

The successful autorotation flight depends on several factors, but the immediate lowering of collective control is paramount within the whole process.

If this action is delayed, the *RPM* of the main rotor may drop beyond the limits set by the manufacturer of the aircraft and, depending on the rotor design, not able to be recovered.

There are two main reasons to establish a minimum *RPM*: (1) the divergence of main rotor *RPM*, below which the upward flow of air through the rotor during descent cannot reverse the behavior of main rotor *RPM* drop rate; (2) increasing the bending moments at the root of the blades, which may undergo severe structural damage and rupture [1].

Thus, it is possible to understand that the action of lowering the collective control has a maximum time delay to be initiated by the pilot, denominated critical time (c_t). If the action is not accomplished in a time lapse inferior to it, there is a penalty of making it impossible the entry in a stabilized autorotation flight.

By definition, critical time is the maximum time in which the flight controls can be held fixed during the transition to autorotation flight [1]. The critical time is limited by the following factors:

a) Minimum main rotor speed;

b) Attitude or angular rates (or combination of both) that allows full recovery of *RPM*; and

c) Conditions to enable the pilot to move the flight controls with the necessary time rate without producing movements or acceleration which lead to exceeding the structural limits.

This article presents only the effect of the minimum *RPM* at the critical time, because, in general, this is the main limiting factor. In this case, the critical time is regarded as the interval between the time of the engine failure and the time at which the pilot starts to reduce the collective control to avoid the main rotor *RPM* drop to a value below the minimum rotation expected.

The main rotor *RPM* drop rate is influenced by the torque applied in the pre-failure moment, which is a consequence of weight, density-altitude, *CG* position and speed of the aircraft; therefore, it is necessary to investigate the critical time in various combinations of factors in order to define the most critical conditions to be validated by flight test.

Thus, following the doctrine of progressive approximation, many test points were performed, with the variation of weight, density-altitude and speed.

In Figure 10 it can be observed that, in the tested conditions, the pilot had to start to lower the collective control with little more than 0.7s. In this case, the alarm would go off just after 0.9s, i.e., the system which should contribute to improving the condition of flight safety did not work very well, because such alarm only would start its operation when it would not be possible to recover the rotation of the helicopter.

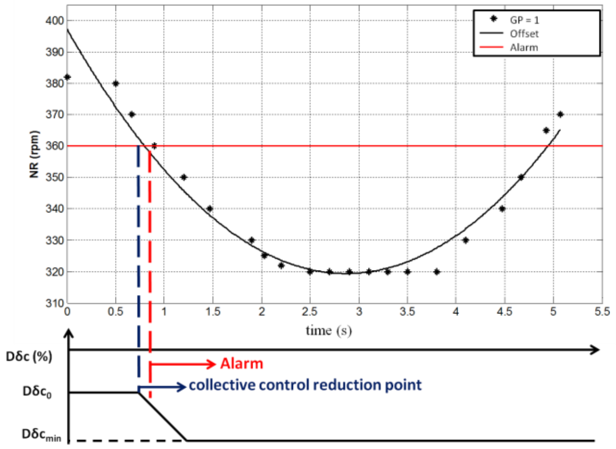


Figure 10: Main rotor *RPM drop* rate.

The direct consequence of such low critical times is the difficulty for the pilot to recognize an engine failure and take the necessary action in a very limited time. The minimum time required for the pilot to react to this failure is denominated reaction time.

2.5.1 Reaction Time

By definition [1], the reaction time (r_t) of the pilot is the elapsed time between the occurrence of engine failure and the response of the pilot on flight controls. Its magnitude varies from pilot to pilot, but as a rule, this variation is minimal. The t_c is a time lapse that follows the pilot visual and vestibular perception and the proprioceptive information resulting from engine failure.

The reaction time is a function of number of delays or time lags. These gaps are related to the reception of the signal, the transmission to the brain, the processing information and the transmission of the order back to members to activation of muscles to move the flight controls. They depend on a number of factors, such as pilot attention, simple warning or set of notices and the combined types of warnings.

Pilots prepared for the imminent engine failure can react in approximately 0.5s. When the pilot is not warned, he can lose more 0.2 to 0.3s, approximately [1].

FAR-27 do not determine adequate and restrictive criteria for the reaction time of the pilot. Paragraph § 27.143 (e) shows:

"... No corrective action time delay for any condition following power failure may be less than—

(i) For the cruise condition, one second, or normal pilot reaction time (whichever is greater); and

(ii) For any other condition, normal pilot reaction time.

But what exactly means cruise condition? What are the quantitative criteria that guide this definition?

What are these "other conditions" and what is a "normal pilot reaction time"?

This type of requirement, in fact, is not aligned with the objective of an aeronautical standardization, since abdicates to define criteria which are closely related to flight safety, as the establishment of the minimum and adequate reaction time to the pilot, for any part of the flight.

In part of the flight tests, the critical time was less than the reaction time of the pilot and reached the safety *RPM* limit before the alarm goes off. This characteristic is aggravated by the fact that the test conditions are strictly controlled and the test pilot participates in the power reduction simulation, which reduces the time required to perceive the failure.

Another fact that is omitted by FAR-27 is the exact moment when the reaction time is computed. The reaction time of 1s starts at the moment of the engine failure or when the alarm goes off? What type of engine failure that the FAR-27 considers default to start the reaction time?

These omissions aggravated by the use of subjective criteria such as "normal reaction time of the pilot" shall be revised and complemented.

It is noteworthy that during a sudden engine failure, the most critical conditions of safety and workload volume occur during takeoff, especially in the "knee" of the dead man's curve, where more time should be guaranteed for the pilot. Once again, the FAR-27 is silent about this requirement.

Considerations and justifications found in the literature which indicate that it is not necessary to establish a higher reaction time on low altitude flights come from the hypothesis that in these conditions, especially during takeoffs, the pilot shall focus his attention on alarms and engine instruments to react more quickly in an emergency situation.

Technically, this hypothesis is not completely true, since any takeoff, for either an airplane or helicopter, in visual or instrumental conditions, the pilot must consider external references, not being appropriate or recommended to carry out this maneuver with all attention focused on the engine instruments and indication of *RPM*.

Moreover, at the moment of failure, the aerodynamic imbalances, enhanced by high torque used for takeoff and low speeds, contribute in turning it even more difficult to perform the emergency procedures.

When takeoff maneuvers are performed in low altitudes they increase the risk of aircraft collision against the ground. In this case, the total lowering of the collective control cannot be performed with the amplitude and time lapse required to allow the reversion of the direction of main rotor *RPM* drop, under penalty of harming the aircraft touching the ground without proper reduction the horizontal and vertical speeds.

During takeoff, maneuvers for deceleration the helicopter, like flare, become even more restricted because the translational kinetic energy available to be converted into rotational kinetic energy is very limited and the capability to control the aircraft decreases with the main rotor *RPM* drop rate, which hinders the achievement of precise maneuvers, increasing the main rotor *RPM* drop, prompting the possibility of causing the touch of the helicopter tail against the ground.

FERRELL, et al. [12] claim that the failures occurred during climbs, at low speeds, are more critical because the turbulent wake of normalwash interferes with the aerodynamic flow on the horizontal stabilizer, causing a momentary instability and increasing the workload of the pilot. This usually occurs during a short takeoff.

The MIL-D-23222A standard [16] is more restrictive, imposing a reaction time of 2s for the pilot to move any of the controls, regardless of the height in which the engine failure occurs.

Therefore, it was possible to analyze and validate the importance and the influence of reaction time to ensure flight safety during a sudden engine failure, demonstrating that the FAR-27 provide an inadequate criterion for the reaction time of the pilot.

2.6 Height-Speed Curve

"Since the actual ability to make a safe landing depends on the interaction between the helicopter and the pilot, the high-velocity diagram can only be accurately determined in flight tests" [3].

The curve which limits the unsafe operations for height and speed combinations is obtained from flight tests, by reducing the fuel flow to the flight idle, in several combinations of height and speed.

The determination of each point of this curve is made following a particular methodology, with a selective control of influential variables, which are: speed, height, weight, temperature, density-altitude and position of the center of gravity.

With the data from the test flights is possible to verify that there are many factors that hinder the safe autorotation flight and are omitted in the main certification standards.

The lack of a definition of the exact time when the reaction time shall be considered, the absence of restricting criteria for the installation of alarms, inadequate definition of reaction time and small reaction time, especially during takeoffs, make the risks unacceptable for flying a single-engine helicopter, certified by FAR-27.

During the flight tests one verified that, during the takeoffs, lower speeds can restrict the maneuvers which should be performed to mitigate the critical landing conditions. The same way, the ground proximity increases the workload of the pilot to avoid a premature touch against the ground.

Depending on the combination of height and speed, sometimes it is not possible to reduce the collective pitch control, which causes a continuous main rotor *RPM* drop rate until landing.

This variation of *RPM*, even remaining above the minimum limit specified by the manufacturer, produces a change in the control capability of the aircraft, which begins to demand larger movements of flight controls in order to generate the same control moments observed in nominal conditions of *RPM*.

Another consequence is that the reduction of *RPM* increases the amplitude of the blades flapping and the actions necessaries to control the tilt of the rotor, which reduces the margin of separation from the fuselage to the rotor.

All these changes, resulting of the drop of the main rotor *RPM* also change the performance of the helicopter, increase the workload and hinder autorotation flight maneuvers.

The methodological process used by the main Flight Test Schools in the world, as USNTPS and EPNER, does not establish the time delay between the simulated engine failure and the pilot reaction, neither the lowering collective control rate. These criteria, depending on the standardization used, can significantly alter the limits of the curve.

Therefore, the height-speed curve, which presents considerable operational restrictions, may not cover all flight profiles that the aircraft experiences at the time of the engine failure.

Considering that this curve is tested with the aircraft in straight and leveled flight, it is possible to estimate that in the same point of the curve, in a given combination of height and speed, the main rotor *RPM* drop rate can present different behavior depending of the flight profiles, like climbing and descents. This is more critical if the aircraft is climbing, with greater torque when compared with the scenarios when the aircraft is in leveled flight or in descent.

Moreover, vertical flight velocities different to zero influences the balance among the gravitational potential energy and translational and rotational kinetic energies, modifying the gradient of the main rotor *RPM* drop rate until the stable autorotation flight be achieved. In addition, high variations in the longitudinal attitudes of the aircraft affect the control moments of the helicopter.

Furthermore, it is important to emphasize that there are other critical factors which are also not covered neither by FAR-27 nor by flight test schools, such as: (1) autorotation during turns; (2) autorotation under night conditions; (3) autorotation over/atop an unprepared terrain, such as landing in water or steep terrain, and (4) autorotation to a restrict area where the landing with little forward speed is needed.

A pilot with median piloting skills, when observing the high-speed curve, believes that he/she will be protected if flying off the unsafe conditions of the figure; however, for the same height-speed combination, the pilot can experience different workloads depending on flight profile at the time of the engine failure (e.g. when high vertical speeds are there). One can say that, indeed, several curves, one for each flight profile, are present, coexisting.

FERRELL, et al. [12] indicates the existence of several curves representing the unsafe areas of the high-speed diagram, relating each curve with a probability of risk, which depends on all influential factors that have been discussed in this research.

Figure 11 proposes, qualitatively, curves for risk levels, which are based on the considerations set out by Ferrel and contributions of this research, which were tested and validated in flight.

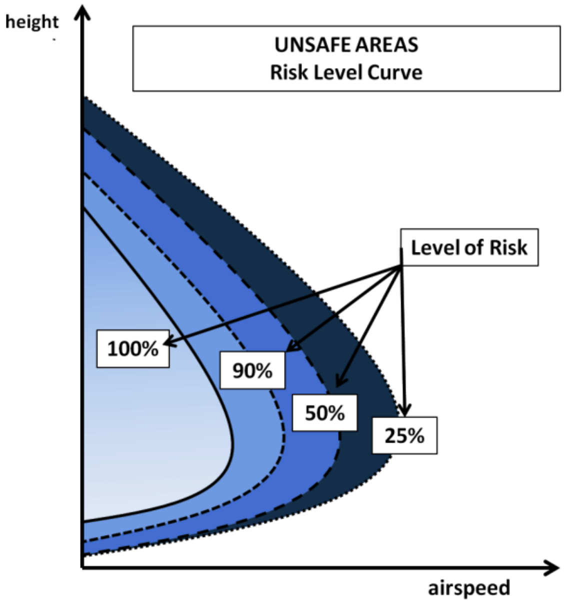


Figure 11: Unsafe area of flight and risk level curve. Adapted from Ferrell et al. [12]

The inner curve, representing the completely unsafe area, is the traditional dead man's curve. The others represent the consequent risks related to workload, training, weather conditions, the flying skills of the pilot, the lowering collective control rate, reaction time, etc.

In fact, it is necessary to clarify this information to the Certification Agencies, manufacturers and operators: the methodologies and requirements present in FAR-27 cannot be safe to fly in all conditions of the flight envelope approved, even respecting the limits of unsafe regions established by the dead man's curve in the aircraft's flight manuals.

So, while there is not a deep revision of the requirements and certification processes based on

FAR-27, there is no guarantee that there is a safe combination of height-speed to fly during a real autorotation- the live man's curve.

CONCLUSIONS

This paper identifies key factors that affect the performance and flying qualities of an aircraft during a full autorotation.

These factors, related to the engine failure; aerodynamic imbalances; alarms, artificial and natural; lowering collective control rate; critical time and height-speed curve, were analyzed in order to know the influence of aircraft design and certification process in workload to carry out the autorotation flight.

The engine can present different types of failures, like seizure or disintegration of the engine shaft, fuel starvation, fuel shut-off and gradual deterioration of the engine. Each of these failures affects the torque drop rate and, hence, the time and the kind of pilot reaction to ingress into an autorotation flight.

Furthermore, during a simulated engine failure, the residual torque available decreases the rate of descent and the aerodynamic imbalance of the helicopter and, therefore, cannot be representative of a real autorotation.

The aerodynamics imbalances show themselves easily controllable at the time of the engine failure, being causing low workload; however, the main rotor *RPM* drop rate increases when the pilot does not move the flight controls immediately after engine failure. In test flights carried out, the reaction time of 1s generated a drop of almost 15% of the maximum permitted main rotor *RPM* drop for the AS-350.

Natural alarms of engine failure proved inefficient, especially on flights with low power, like the final approach for landing, where small angular variations could go unnoticed by the pilot. Therefore, alarms may go unnoticed or be ambiguous enough to not alarm the pilot in time to react.

Artificial alarms were more efficient, especially when they have the aural and voice warning systems.

Thus, following the analysis of the influence of the alarms of engine failure, it is possible to confirm the importance of having a clear, adequate, dedicated and unequivocal sign of engine failure, preferably associated with an aural warning.

The time elapse to lower the collective control also revealed an influence on the success of autorotation flight. The flight tests showed that the main rotor *RPM* drop rate is directly proportional to the time lapse to lower the collective, i.e., the slower lowering the collective control, the greater the drop of main rotor *RPM*.

The critical time and reaction time were the key points showing themselves as influence the success of autorotation flight, presenting the less conservative criteria data of FAR-27 associated requirements.

In some flight profiles such as takeoffs, low speeds and heights hinder the exchange of potential and kinetic energy per *RPM*. Moreover, in these conditions, the collective lever cannot be lowered completely what increases the main rotor *RPM* drop rate.

At some points of the test flights, the reaction time was lower than the critical time, which meant that the *RPM* below the minimum established by the manufacturer of the aircraft if the pilot had not immediately move the collective control.

Finally, the evaluation of the height-speed diagram and all influential factors revealed that the current methodology and the non-conservative criteria of FAR-27 do not guarantee the existence of only one dead man's curve.

This research, then, proposes a determination of the risk level diagram, instead of the traditional dead man’s curve. This diagram shall consider the influence of the consequent risks related to workload, training, weather conditions, flying skills of the pilot, lowering collective control rate and reaction time.

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