Alternative procedure to verify the H–V diagram after external installations on helicopters

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ORIGINAL PAPER

Alternative procedure to verify the H–V diagram after external installations on helicopters

Manuela Battipede[1] · Raffaele Di Caprio[2] · Manfred Bleyer[3] · Matteo Vazzola[4]

Abstract

Certification of external installations on helicopters, for modifications for which CS27/29.865 is not applicable, often requires the showing of compliance of paragraph CS XX.79—limiting height-speed envelope—which might imply, ultimately, a certain degree of H–V testing. Due to the implications on safety during the investigation of the H–V curve, a preliminary analytical investigation is advisable, to understand whether H–V test can be drastically reduced. Analytical investigation, though, is usually based on the extensive use of simulation data, based on validated dynamic mathematical models, which are usually not available to the applicant. The authors recently proposed an alternative method, based on the analysis of a set of flight tests, which is meant to assess quantitatively the different phases of the physical/mechanical phenomena related to the emergency maneuver performed by the pilot as a consequence of a power loss, within or in the proximity of the H–V curve. More in details, the analysis of the autorotation phenomenology reveals that the maneuver is made up by different phases and dedicated tests have been proposed to assess each of these phases. The whole test campaign is hence meant to gain a thorough insight of how, and specifically in which part of the maneuver, the external modification could affect the helicopter H–V characteristic. Depending on this substantiation, H–V testing can be avoided or drastically reduced, limiting the investigation to a few meaningful points. The proposed method has been recently assessed on an external basket installation, making use of purposely developed Flight Instrumentation and post-processing tools. More in details, results and conclusions are based on the analysis of static and dynamic flight parameters, acquired with a non-intrusive Flight Test Instrumentation, which monitors and correlates cockpit parameters and flight commands, following a back-to-back approach (i.e., pre- and post-modification). The method demonstrated was witnessed by EASA and found acceptable as an alternative method for showing of compliance to the applicable requirements.

Keywords H–V curve · Safety · Alternative mean of compliance · External installation · STC

No footnotes concerning this paper is based on a presentation.

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Abbreviations

AEO	All engines operative
AGL	Above ground level
CAS	Calibrated airspeed
CG	Center of gravity
CS	Certification specifications
Hd	Density altitude
Hp	Pressure altitude
H–V	Height–velocity
FAQ	Frequently asked questions
FC	Flight conditions
GW	Gross weight
IAS	Indicated air speed
IGE	In ground effect
I_{yy}	Longitudinal moment of inertia
I_R	Rotor inertia
KIAS	Indicated airspeed in kt

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LFTE	Lead flight test engineer
LH	Left hand
MTOW	Maximum take-off weight
N_r	Main rotor speed
OAT	Outside air temperature
OEI	One engine inoperative
OGE	Out of ground effect
RFM	Rotorcraft flight manual
RH	Right hand
ROC	Rate of climb
ROD	Rate of descent
RPM	Revolutions per minute
SL	See level
STC	Supplemental type certificate
TC	Type certificate
TP	Test pilot
TQ	Torque
VFR	Visual flight rules
V_Y	Speed of maximum ROC
Ω	Rotor speed
σ	Air density

Fig. 1 Asymmetrical single-basket configurations

Fig. 2 Symmetrical dual-basket configuration

1 Introduction

A request was made to a Part 21-Subpart J [1] Design Organization Approval, by a helicopter operator, to certify the external installation of one or two purposely manufactured baskets on the AS350 series, including the AS350 B1, B2, B3 and B3e series, to increase the payload volume capacity up to 0.140 m^3 for each basket.

Each of the two baskets can be positioned on the helicopter skid with an upward opening and mounted in an asymmetrical configuration (left or right single basket, Fig. 1) or in a symmetrical configuration (dual basket, Fig. 2).

Increasing the external helicopter volume capacity is in constant demand among the helicopter operators, as carrying hazardous, dirty or cumbersome items outside the helicopter is considered crucial in a variety of helicopter operations. The installation of external pods or baskets, however, normally implies that the total weight payload capacity must respect the limitations indicated by the manufacturer, or TC Holder, in the Flight Manual. As each helicopter is certified for a maximum take-off weight (MTOW), these limitations are given in terms of combinations of weight and center of gravity positions, both for the longitudinal and lateral plane. An increase of external volume, hence, does not imply an increase of the total helicopter MTOW or payload weight capacity. On the contrary: the certification process of the kit installation is meant to demonstrate that the installed kit does not jeopardize the helicopter airworthiness under the

existing limitations or, in case, under new restrictive limitations, identified during the certification program.

According to EASA Part 21 [1], this modification is considered a major change, which implies that a certain number of affected structural and flight requirements of EASA/FAA technical regulation needs to be re-assessed.

In 2019, to support the industry involved in compliance demonstration of major changes or STC, EASA issued the *Certification Memorandum on External Installations on Helicopters* [2]. The memorandum was issued specifically for helicopter external modifications, to provide the Design

Organizations with specific Guidance Material for the certification of external installations that can be considered non-extensive in terms of weight, external surface and/or volume.

The Memorandum indicates flight testing as the most viable mean to obtain evidence and show compliance with the affected requirements of the certification specifications.

Extensive technical consultation among the parties involved in the definition of the certification program, though, was dedicated to a specific paragraph of the memorandum, which indicates that for modifications for which CS 27/29.865[1] is not applicable, height–velocity diagram investigation must be performed to show compliance with requirement CS 27/29.79.

Flight test investigation of the height–velocity curve, if executed as indicated by the reference Guidance Material [4], involves a certain number of autorotation landings from low-speed, low-altitude initial points, that, even in the most conservative buildup approach, involve a substantial inherent risk [5].

The autorotation landing is basically composed of three phases. The first phase starts immediately after the engine failure, when the rotor slows down, since it is no longer sustained to oppose the torque produced by the drag on the blades. The pilot has to react as soon as possible performing a non-instinctive maneuver consisting of the quick reduction of the collective pitch: by reducing the blade pitch, the rotor drag decreases and the resultant of the aerodynamic forces can rotate forward, to propel the blade and increase the rotor speed. In this phase, the pilot has to enter a dive and gain speed. The second phase starts when the steady autorotation is established and the airflow, directed upward through the descending rotor, provides the energy to maintain the rotor angular speed. The third phase is started by the pilot, upon approaching the ground: with a pitch-up maneuver, the helicopter is rapidly decelerated to a forward speed compatible with a safe touch down. At this point, the pilot can level the helicopter and land, with the rotor speed decreasing substantially.

If handled properly, an autorotation landing can be performed successfully, as long as the helicopter maintains lateral control and the height and speed are adequate to complete the maneuver. As an emergency procedure in case of engine power loss on a single-engine helicopter, the pilot is trained to immediately start the maneuver to enter autorotation and land the helicopter.

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[1] CS 27/29.865 is the current EASA certification requirement for Helicopters carrying external loads, such as human external cargo—HEC—or nonhuman external cargo—NHEC. Guidance for new applications for carrying of external loads under CS 27/29.865 is given in the dedicated Certification Memorandum [3].

As for the current regulations, the height–velocity (H–V) curve, otherwise defined as dead man's curve, determines the envelope of the combination of height and forward speed, including hover, under which a safe landing cannot be made, because the potential and kinetic energy available is not enough to cushion the vertical speed below the limiting sink rate of the landing gear.

H–V is the least predictable of all rotorcraft performance and, during the certification program, the ultimate accepted H–V curve is what can be actually demonstrated with flight testing. H–V testing, especially the one performed during the initial TC investigation, usually involves measurement and recording of all possible flight parameters, performed either with ground and airborne test equipment. As per the Guidance Material [4], weight extrapolation is not permitted, which implies that test weight must be closely controlled. The extrapolation of test data to different density altitudes is limited to 2000 ft and must be supported by an approved analytical or simulation method. Pass/Fail criteria of the test points are related mainly to excessive gear loads, exceptional skill requirements, winds above permissible levels, rotor droop below approved minimum transient RPM, damage to the rotorcraft, excessive power and incorrect time delay.

The pilot workload, which can be physical, if related to the control activity, or cognitive, if related to the effort in maintaining the concentration, is usually given either in a narrative format or determined using objective methods (i.e., Cooper Harper [6] and Bedford [7]) Experimental research conducted to evaluate the pilot workload during emergency autorotation landings [8] have been partially successful in selecting specific objective parameters, which could be used for workload quantification during an autorotation landing in the proximity of the H–V curve. Nevertheless, these studies have outlined that some parts of the H–V diagram are more demanding in terms of control activity and, as a consequence, more critical in terms of the risks involved in flight testing.

This paper describes the flight testing technique that has been proposed to mitigate the risk involved in the actual H–V diagram testing, by eliminating or reducing substantially the number of actual test points in autorotation landings, for modifications for which the Certification Memorandum of Ref. [2] is applicable.

2 Height–velocity (H–V) curve

The H–V curve is a characteristic of the specific helicopter and is duly reported on the published TC Holder Flight Manual, to delimit a flight envelope for which safe landing would not be possible following an engine failure. Although helicopter operations often require flying within the H–V curve, the basic recommendation for the pilot, on a single-engine

Table 1 Airspeed-height envelope [12]

Point	Condition (at SL)
A	Constant zero airspeed Variable height depending on the density altitude and on the aircraft weight
B	Constant height of 100 ft (30 m) Variable airspeed, depending on the density altitude and on the aircraft weight
C	25 ft (9 m) at 40 knots (74 km/h)
D	8 ft (2.5 m) at zero airspeed
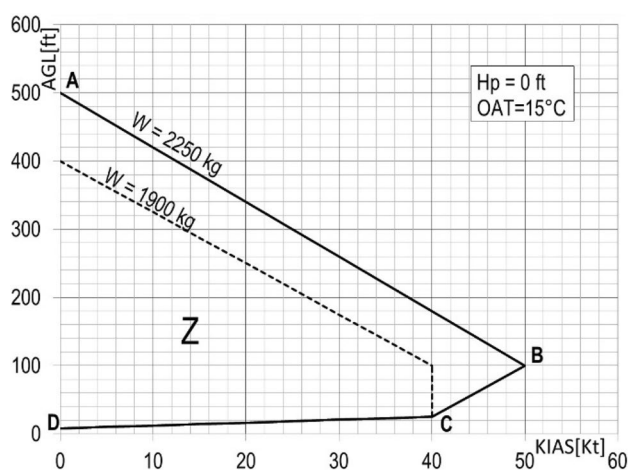
Fig. 3 H–V diagram [12]

helicopter, is to simply avoid continuous operation within the avoidance area whenever possible.

Independently from the specific helicopter, the avoidance zone (Z) is defined by the four points A, B, C, D. Table 1 and Fig. 3 report the specific case of the AS350 [12]. Figure 3, in particular, refers to a precise helicopter weight-density altitude combination, but will enlarge or reduce according to the indications given in the TC Holder FM.

Point B, also known as the 'knee point', is the most critical point of the H–V curve, as it involves a very low ground height, and hence low potential energy, combined with a rotorcraft speed which gives a very low kinetic energy level. The knee point separates the low-altitude portion, also known as the take-off portion, from the higher altitude, also known as the cruise portion, of the H–V curve.

During the certification program of a new Type Certificate, the H–V curve investigation generally involves the preliminary use of analytical methods, which are mainly employed to estimate whether, for the combination of selected height and speed values, the maneuver could be potentially performed with enough margins in the

control excursions, to contrast random gusts which might be encountered in the calm wind environment (3 knots or less), required for H–V testing. Analytical methods, de facto, are used to mitigate the risks associated with the maneuver execution.

H–V analytical tools are commonly based upon nonlinear optimal control theory due to the complexity of the maneuver that must be performed to obtain a safe landing. As pointed out by Johnson in ref. [9], in fact, there are many design indices or parameters influencing the helicopter autorotative performance, but their effect can be easily obscured by a poor selection of the control law implemented by the pilot. Nonlinear optimal control theory is used to establish the best control schedule, to analyze the most relevant design indexes and parameters, eliminating the influence of the pilot control choice. The various H–V analytical tools deriving from the initial Johnson method [9] rely on a point-mass dynamic model, incorporating the helicopter properties, to account for the mass-power helicopter characteristics, the rotor stall, the vortex ring state and the lag in the power drop after the engine shutdown. The proposed versions of the tool [10] differ mainly for the selection of the quadratic cost function and the boundary conditions, resulting in a better or worse correlation with the test data which depends on the specific part of the H–V curve that is analyzed.

When applied to the last part of the maneuver, Fradenburgh [11] found a high correlation with a proposed flare index and the pilot opinion on the helicopter autorotation landing properties.

On a more practical level, semiempirical procedures have been developed to mathematically extrapolate the data collected during flight tests, to calculate parts of the H–V curve with the same accuracy of the initial flight test data. The precursor is the Pegg method [13], specifically developed to address the low-speed part of the H–V curve. An application and extension of the Pegg method [13] was at the base of the test campaign presented in [14], for the military qualification of a new main rotor blade model for the TH-500 helicopter. The application of the method was crucial to reduce the number of effective autorotation touchdowns performed under the most critical conditions, thus reducing heavy loads on the landing skid, pilot fatigue and generally improving safety.

3 Alternative method for showing of compliance

The key point of the proposed alternative method to show compliance with requirement CS 27.79, after the embodiment of an external installation, is to investigate all the phases of the autorotation landing and analyze whether the embodiment of the external installation could have an
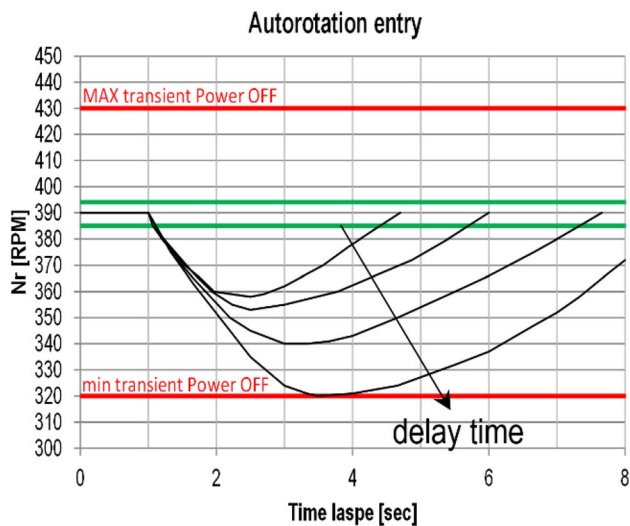
Fig. 4 Effect of delay or reaction time on rotor speed in autorotation

Fig. 5 Glide: transient form from the autorotation entering to the minimum RoD speed

impact on any of them. The analysis of the H–V curve is then carried out through the quantitative measurement of specific performance parameters, as outlined hereinafter. The autorotation phenomenology reveals that the impact of an external installation on the H–V curve can be assessed by analyzing the following four performance characteristics:

- Out-of-Ground-Effect (OGE) and In-Ground-Effect (IGE) hover: in this phase, the key characteristic parameter is the power required to hover, which is measured through the torque level, related to the actual helicopter weight;
- Transition phase from the Power ON and Power OFF conditions (autorotation entry phase): in this phase the key characteristic is the time history of the rotor speed N_r measured starting immediately after the engine loss up to the moment the pilot succeeds in bringing the rotor speed back within the acceptable range, performing the maneuver to enter autorotation after the necessary reaction time (Fig. 4);
- Autorotation descent: after a power loss in hovering, the key characteristic is the ability to accelerate to the speed of minimum rate of descent (ROD), which is approximately equal to the speed of maximum rate of climb (ROC) V_Y. To quantitatively assess the acceleration characteristics in this phase, measurements are focused on the loss of altitude ΔH (Fig. 5) necessary to accelerate, in a glide, the rotorcraft in autorotation from 0 to the speed V_Y;
- Flare: this phase can be assessed qualitatively in terms of the effectiveness of the flare maneuver in producing both a vertical and longitudinal deceleration.
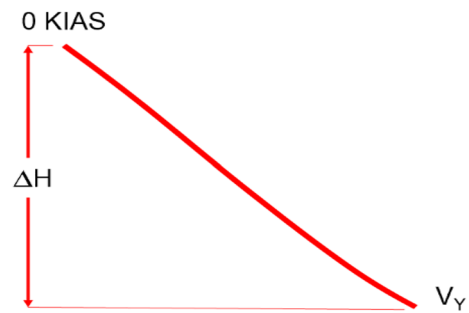
In performance assessment, the Certification Memorandum on External Installations on Helicopters [2] guides the applicants in a very practical way, endorsing a few testing approaches which have proven to be effective and consistent with the consolidated Guidance Material contained in Ref. [4].

A sound approach encouraged by the memorandum to show compliance with the performance requirements is known as the 'back-to-back' approach, which is specifically meant to assess the effects of the modification on performance. The method consists of selecting a limited number of meaningful flight conditions and aircraft CG-weight combinations, which are typically recognized as the most critical ones. The concept of 'most critical' is always referred to the conditions that are more affected than others by the modification, for the specific certification specification, in the envelope for which certification is sought. The test must be performed for both the unmodified (or baseline) and modified configurations and the collected data must undergo the data reduction process, in order to be referred to the very same flight condition, in terms of speed, density altitude and CG-weight combination. Comparison of results will indicate whether the modification has a negligible effect on the specific performance requirement, or if there is a degradation and, in this case, what is the extent of this degradation. For some performance requirements, for example climbing, a reduction in the performance parameter (rate of climb) can be considered acceptable, provided it is estimated and systematically reported in the Flight Manual performance section. To that end, the applicant will issue a Flight Manual Supplement, which supersedes or completes the information given by the manufacturer. Both the FAA and EASA Guidance Material proposes practical and validated methods for generalizing the results obtained in a limited number of flight conditions to the whole flight envelope, with the general recommendation that the process must be conservative. The back-to-back method is particularly attractive for applicants that are not the TC Holder of the aircraft involved in the modification:

a detailed assessment of the modified configuration, in fact, would require the knowledge of design parameters, such as the minimum spec engine,[2] for example, which are usually not disclosed by the TC Holder. It is intended that the manufacture's published performance is the minimum guaranteed and are obtained at the minimum spec engine, for each indicated power level (take-off power, maximum continuous power…). Performance measured by the applicant might be slightly different and one of the many sources of discrepancy related to flight testing can be that the engine is performing slightly better than the minimum guaranteed for that specific flight condition.

With reference to the proposed alternative method to show compliance with requirement CS 27.79, the back-to-back method can be used very effectively to quantitatively assess the key performance parameters, with standard maneuvers which can be consistently and safely repeated by a test pilot. In case that no substantial differences are detected in the key performance parameters of the baseline and modified configurations, it can be deduced that the H–V curve is not affected by the change. In this case, compliance with requirement CS 27.79 can be demonstrated, without conducting any complete engine-out landings, especially in the proximity of the H–V curve. According to the proposed alternative means of compliance, in fact, all testing involving engine failure simulation can be performed at a safe height above terrain, since there is no requirement to demonstrate a full autorotation landing, starting from specific height/speed points as required for the full H–V curve demonstration.

The complete investigation of the H–V curve, in particular, is usually performed at the maximum take-off mass, involving at least two density altitudes, for low and high-altitude fields, using a proper buildup approach in speed and height. Often accessing high-altitude sites for H–V testing can be impracticable or overly expensive as it implies moving the helicopter test campaign on airports where the ground conditions are equivalent to a density altitude of 7000 ft and these sites might be extremely remote or unavailable.

The proposed test method can be a strategic methodology for STC certification investigation, as it does not require performing tests at high-altitude sites, to gather data for the demonstration of the H–V diagram up to the maximum take-off and landing altitude.

In helicopter external modifications, for which the back-to-back comparison can be used to estimate the impact of the modification on performance, the proposed method can offer a valid and practicable quantitative alternative to the actual investigation of the H–V curve, which remains a high-risk

maneuver, difficult to perform in a consistent and repeatable way.

In case even small differences emerge in the comparison of the key performance parameters, though, the proposed method will not be effective in demonstrating compliance to CS 27/29.79 and H–V testing should be reintroduced and performed as required by the Certification Memorandum [2]. The results of this preliminary experimental analysis, however, could be used to mitigate the risk associated to the actual H–V curve investigation, through a substantial reduction of the number of test points, as only the affected and relevant parts of the H–V curve would require actual verification.

4 Preliminary analysis

A preliminary investigation, based on analysis and engineering judgment, was performed to assess the impact of the modification and to substantiate the safety of flight for the Flight Conditions approval. The test campaign was dedicated to the showing of compliance with the affected performance and handling qualities requirements of CS 27, as indicated in the Certification Memorandum [2]. Additional tests were scheduled for the evaluation of the proposed alternative method to show compliance with requirement CS 27/29.79.

As mentioned above, the H–V curve verification implies testing whether, in the case of a sudden power loss and within specific limitations of altitude and speed, the rotor maintains enough energy for entering the autorotation in a forward descending trajectory. Autorotation usually precedes flare and landing, that must be performed while maintaining the vertical and forward speeds within acceptable limits.

In more detail, in the case of a power loss, the rotor torque will be reduced, causing a rotor speed decay. The initial rotor speed decay rate can be estimated by the following equation:

$$\dot{\Omega} = \frac{\Delta TQ}{I_R}$$

where ΔTQ is the resultant of the rotor torque (which is unbalanced because of the torque drop) and I_R is the rotor inertia. As outlined in Sect. 1, the maneuver to enter autorotation consists in the sudden reduction of the collective pitch: by reducing the blade pitch, in fact, the rotor drag can be reduced and the resultant of the aerodynamic forces will act in the direction of propelling the blades and substitute the engine torque to increase the rotor speed. The pilot has to enter a dive to increase the helicopter speed and allow the air to flow efficiently upwards through the rotor and energize the blade rotation. The use of the cyclic control counteracts the helicopter tendency to pitch down, or pitch

Fig. 6 N_r range limitations in flight (inner region, in green) and autorotation (outer region, in red)

up, depending on the helicopter and the actual CG position. In steady autorotation, a given combination of collective pitch, helicopter pitch attitude and airspeed will cause the helicopter to settle on a unique descent speed and rotor speed combination. During the glide, in fact, the pilot can control the rotor speed, commonly referred to as rotor *RPM*, using the collective blade pitch lever: the lower the blade pitch the higher the rotor speed. In practice, however, the usable range of rotor speed is limited. If the rotor speed is too low the blade will stall. If it increases over the prescribed upper limits, loads on the rotor hub and blade roots could exceed the structural limits. The allowed range of rotor RPM is for transient excursions usually within 80 and 120% of the nominal Power ON speed, whereas, for stabilized conditions, it can vary between 90 and 110%.

For the AS350 B2, B3 and B3e series, these values are indicated by the TC Holder RFM [12] as 320 and 430 RPM for the transient, as indicated in Fig. 6 by the red arc, and 370 and 410 RPM for the stabilized autorotation.

The scientific literature [15] reports that factors affecting the rotor speed decay are manifold, including the rotor inertia, the rotor speed and torque values at the instant of the power loss and the ratio of the thrust required over the maximum thrust that the rotor can produce. In particular, beneficial impacts on safety, from the rotor speed decay point of view, can be obtained by increasing the rotor inertia, increasing the nominal rotor speed or by increasing the thrust produced by the rotor in normal conditions.

Important additional factors include the action of the pilot in attempting to contain the rotor speed within the limits and the effect of the rate of descent on the angle of attack of the rotor blades, which will depend on the blade pitch.

In more practical terms, the pilot will try to reduce the rotor speed decay and contain the rotor speed within the limits by quickly lowering the collective pitch. This maneuver has the effect of increasing the rate of descent, while reducing and finally reversing the decelerating torque applied to the rotor. The important key is, hence, the reaction or delay time, defined as the time between an engine failure and the pilot commencing the corrective action, by rapidly lowering the collective lever. The maximum delay time is the delay that causes the rotor speed to reach the minimum Power OFF transient value before reversing the trend to achieve a stable autorotative condition (Fig. 4).

FAA AC27.79 [4], which contains the acceptable means of compliance for the CS27.79 requirement, indicates that flight testing for demonstrating the H–V curve should be conducted using a minimum time delay of 1 s between engine-out simulation and control actuation for the point above the knee. Below the knee, the normal pilot reaction time could be used.

In the preliminary analysis, the effect of the embodiment of the baskets was assessed for all the corner points of the H–V curve of Fig. 3, with the purpose of giving a physical substantiation to the proposed alternative mean of compliance, for the specific external modification. For the back-to-back comparison of the key performance parameters indicated by the proposed alternative mean of compliance, the symmetrical configuration with dual baskets was taken as the worst-case scenario of the modified configurations. It was considered to be the most critical for performance because it involves a greater increase in drag and a significant blockage of the rotor inflow.

Point A and point D are related to an engine loss occurring when the helicopter is hovering, respectively, Out-of-Ground-Effect (OGE) and In-Ground-Effect (IGE). It was estimated that the embodiment of the baskets could have had an impact on drag increasing, in case the rotorcraft speed was above a minimum value. In point A and D, this effect is not detectable. Chances were, however, that a difference in the power required to maintain the hover condition was detected, as the presence of the basket could have had an effect on the induced velocity distributions and, ultimately, on the dynamics which proceed the entrance in autorotation. This effect was expected to be proportional to the percentage of the rotor area affected by the basket potential blockage.

From the analysis of Fig. 7, it was noticed that the baskets are external to the fuselage footprint. In particular, part of the basket footprint is within the hub disk, which is 24% of the disk radius or 10% of the rotor area. The remaining part of the basket footprint is confined between the hub radius and a distance which is about 32% of the total rotor radius. Considering that only about 30% of the 360 degrees blade rotation is affected by the presence of the baskets, it was estimated that the baskets would hence affect, in total, only
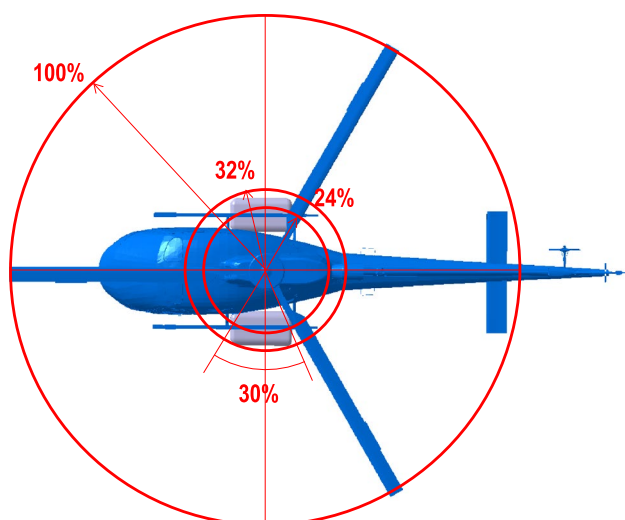
Fig. 7 Basket footprint

Fig. 8 Performance in hovering IGE and OGE for the baseline (in red) and modified (in blue) configurations

1.5% of the disk area which is effective in producing the aerodynamic forces.

Even if this rough estimation suggested that the effect on the hover condition could be negligible, the hover power was indicated as a performance parameter to be measured for comparison, between the baseline and the modified configurations, in the same condition of weight and density altitude.

From point A to point B, the knee point, the speed increases and the effect of extra drag and lift on the baskets was considered more and more detectable and influential during the autorotation descent. The evaluation of the effect of the kit embodiment on the acceleration characteristics, as indicated in Sect. 3, was considered influential and critical, to predict the behavior of the modified helicopter in this part of the H–V curve.

Points from C to D are at very low ground height: for these combinations of height and speed, it was estimated that the presence of the baskets was irrelevant, if not be beneficial. With the kit installed, in fact, there is a wider resistant surface to slow down the rotorcraft drop after the power loss, while the maximum weight remains unchanged.

5 Data analysis

The flight test campaign was performed in two phases. During the first one, in February 2019, specific tests were planned and performed to investigate the four different above-mentioned phases and to gather data to give quantitative evidence to support of the proposed method. During the second of phase, in July 2019, the tests were repeated to validate the results obtained during the first campaign.
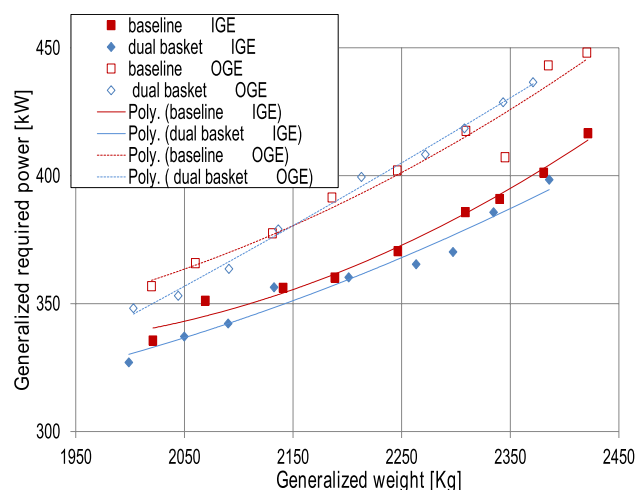
5.1 Hovering IGE/OGE

According to the back-to-back performance assessment approach, hovering IGE/OGE was analyzed both for the baseline and modified configurations. The objective of hover performance tests was to determine the power required to hover in and out of ground effect at different gross weights, with particular relevance for the maximum take-off mass, to assess the low as well the high hover points of the H–V curve. Hover performance tests were executed with the free hover flight test technique [16].

Helicopter gross weight was varied starting from the maximum take-off weight of 2250–1822 kg, by removing ballast and/or crew at each test point and with fuel consumption. This procedure allowed data to be produces related to a generalized gross weight $GW/\sigma N_r^2$ spanning from 1948 to 2421 kg.

The results of Fig. 8 shows that the two curves related to the OGE hover performance are almost coincident, which indicates that the presence of the baskets does not affect the OGE hover performance. This means that, in case of an engine failure in the hover (high hover for the H–V curve), autorotation could potentially start from the same rotor disk load distribution and with the same initial torque, hence producing the same initial rotor speed decay.

For the analysis of Fig. 8, it can be stated that for the IGE hover the presence of the baskets is beneficial. The slightly lower power level required to hover, in fact, indicates a buoyancy effect produced by the presence of the basket, which could be effective in containing the helicopter vertical drop speed, in case of engine loss in the low hovering point D of Fig. 3.
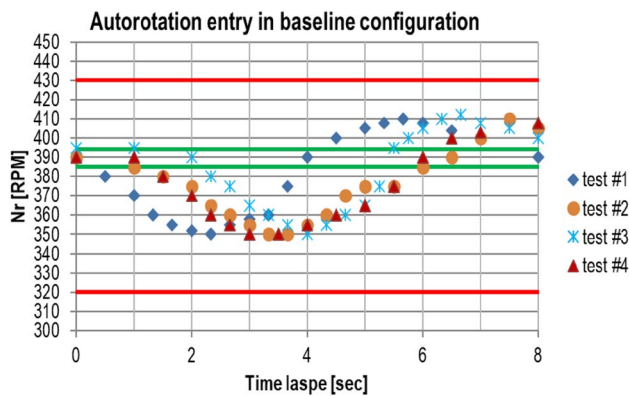
Fig. 9 Transient form engine stop to autorotation entering—baseline configuration

Fig. 10 Transient form engine stop to autorotation entering—symmetrical dual-basket configuration

5.2 Autorotation entering

The assessment of the effect of the embodiment of the change on the autorotation time delay is essential in the H–V curve analysis. To that end, a comparison was performed between the clean helicopter configuration (baseline) and the modified helicopter configuration (both single and dual basket).

As a safety precaution, prior to starting the H–V testing multiple full touchdown autorotations were performed from various altitudes. The helicopter was at maximum gross mass for all the tested configurations.

The test consisted in a series of maneuvers to enter autorotation starting from the hover condition. The LFTE initiated a simulated engine failure by rapidly retarding the fuel control lever to a 'ground idle position'. A minimum of 1 s delay between the initiated power loss and control actuation was utilized. Following the time delay, the collective was lowered and height loss in relation to the time needed to achieve a speed in the range of *50* to 55 KIAS was measured. Rotor speed decay was monitored and video recorded. Upon reaching about 50 KIAS, the autorotation was recovered by adding engine power via the fuel control lever. This procedure was repeated at least three times for each configuration, and opposite headings, to average the results and eliminate the effect of the wind.

During these tests, two different time frames have been analyzed:

- the transient from the engine simulated power loss to the autorotation entry;
- the transient from the autorotation entry to the V_Y speed.

Results for the transient from the engine stop to the autorotation entering are presented in Fig. 9 for the baseline configuration and Fig. 10 for the symmetrical dual-basket configuration. Figure 11 is related to the asymmetrical
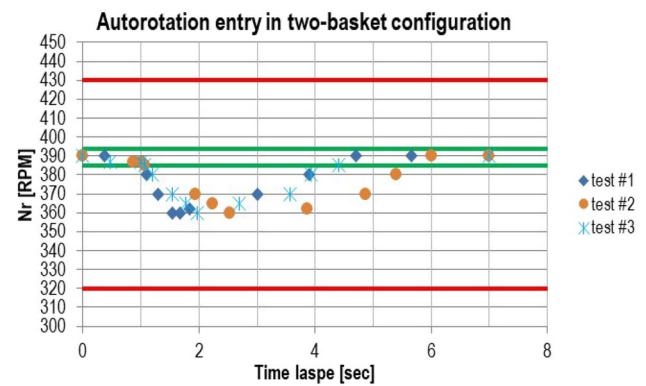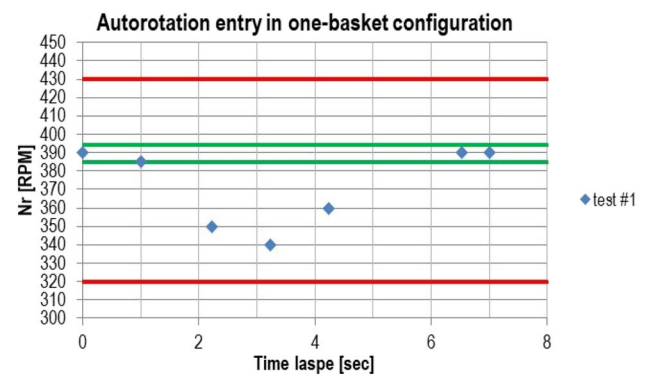

Fig. 11 Transient form engine stop to autorotation entering—asymmetrical one basket configuration

single-basket configuration and is reported for completeness, as the dual basket is considered much more relevant in performance evaluation.

Data have been collected with a post flight analysis of the recorded video and plotted to show how and when the reduction of N_r reaches the minimum transient power-off rotor speed, with the limitations given in [12] (refer to the B2 model).

It should be noted that among the autorotation entry tests performed in all the configurations, only the most significant results have been reported.

For all the configurations tested, the autorotation minimum rotor speed is never reached and the autorotation is stabilized within 8–9 s form the engine stop. The time histories of Fig. 9, related to the baseline configuration, present an overshoot in the N_r signal, which is not visible for the modified configurations. This difference is mainly related to the conservative built-up approach, that was adopted for the tests, which started on the baseline configuration and ended with the more critical asymmetrical configuration. While performing the tests, the flight crew became more and more

Table 2 Transient from the autorotation entering to the $V_y = 55$ KIAS at high altitude (hover stabilized at Hp 8000 ft)

Conf.	Hp in (ft)	Hp fin (ft)	Time (s)	ΔH (ft)	Avg. time (s)	Avg ΔH (ft)
Modified asymm (single basket)	8000	7700	10.99	300	11.17	300.00
	8000	7700	11.19	300		
	8000	7700	11.33	300		
Modified symm (dual baskets)	8000	7650	10.61	350	11.79	316.67
	8000	7700	12.32	300		
	8000	7700	12.44	300		

Table 3 Transient from the autorotation entering to the $V_y = 50$ KIAS at low-altitude (hover stabilized at 1000 ft AGL)

Conf.	Hp in (ft)	Hp fin (ft)	Time (s)	ΔH (ft)	Avg. time (s)	Avg ΔH (ft)
Baseline	1600	1400	8	200	9.00	190.00
	1670	1480	9	190		
	1600	1420	10	180		
Modified symm (Dual baskets)	1630	1400	10	230	9.05	203.33
	1560	1380	7.66	180		
	1600	1400	9.5	200		

proficient in performing the maneuver with the test article and the time histories developed into the smoother trends of Figs. 10 and 11. Even with the N_r overshoot, however, the time histories remain well confined within the boundaries of the transient excursions and this is verified for all the configurations.

To analyze the transient from the autorotation entry to the minimum RoD speed, data were collected in both phases of the flight testing.

In particular, results reported in Table 2 refer to the first phase, performed in February, in a particularly cold and snowy season, with the following initial conditions:

- MTOW = 2250 kg
- aft CG
- Hp = 8000 ft

As a reference final speed test, $V_y = 55$ KIAS was selected.

Results reported in Table 3 are related to the second phase of the flight testing, performed in July, with temperature ranging from 30 to 35 °C. The decision to perform the second phase at a much lower Hp was both because of the extreme difference in temperature and to reduce the mission time. In particular, results refer to the following initial conditions:

- MTOW = 2250 kg
- Centre CG

- 1000 AGL (H_p was approximately 1600 ft, with H_d ranging from 3600 to 4300 ft)

As a reference final speed test $V_y = 50$ KIAS was selected, to reduce the altitude loss during the tests.

The results reveal that the behavior of the rotorcraft in both the configurations is comparable and acceptable.

There is a slight difference in the altitude loss: it can be noticed that the modified configuration reaches the target speed after larger altitude losses and this can be related to the extra drag introduced by the baskets, and in fact the dual-basket configuration, in this respect, performs a bit worse than the single-basket configuration. Differences in the transient dynamics, however, are of the order of a few percentage points in terms of altitude loss, which is negligible when compared to the maneuver as a whole. The small difference calculated in the altitude drop, moreover, derives from a few scattered points, whereas the majority of the test's points are fully comparable.

5.3 Flare

Flare characteristics were investigated in a qualitative way during purposely planned tests. Tests were conducted at low altitude performing a high number of quick stop maneuvers at different speeds and flare angles for the three configurations: baseline, modified with single basket and with dual baskets. The Test Pilot commented that there was

no noticeable difference in the stopping distance and in the effort required to flare the helicopter. This can be easily explained, just considering that the extra drag introduced by the baskets is almost negligible at the flare speed and that the extra inertia introduced by the fully loaded baskets (90 kg each) can be estimate as the 2% of the total I_{yy} inertia relevant for the pitch-up maneuver.

6 Discussion

For the proposed installation, on the basis of the flight test data collected in both phases of the test campaign, consisting in a total of about 30 test points, it could be assessed that:

- the IGE and OGE hover tests do not show a reduction in hover performance. In particular for the OGE hover, the torque required for flying in the low-speed regime is unchanged, producing no change in the initial rotor speed decay rate following an engine failure;
- there is no significant change in the autorotation entry characteristics of the helicopter, with similar rotor speed recovery features and comparable acceleration characteristics towards the minimum descent rate speed V_y, for the autorotation, in terms of height loss;
- The glide performance at V_y remain unchanged, which means that success in maintaining a steady autorotation, also in the proximity of the H–V curve, relies only on the Pilot's ability to perform an optimal maneuver. The small difference calculated in the altitude loss was considered acceptable in the economy of the whole maneuver, also considering that the majority of the tests where comparable apart from a few scattered points;
- The flare characteristics of the helicopter in the baseline and modified configurations are comparable.

Therefore, it could be demonstrated that with the new configuration the helicopter performance and handling characteristics affecting the autorotation maneuver remain unchanged compared to the baseline certified configuration, ensuring the capability of the helicopter to perform a safe autorotational landing from any point of the H–V curve.

Based on the above, it could be concluded that the H–V curve for the proposed installation is basically unchanged with respect to the baseline certified configuration.

In this case, the alternative proposed method has allowed the compliance demonstration to be performed with major benefits both in terms of safety and cost efficiency. In particular, no complete engine-out landing, starting from the edge of the H–V curve or in its proximity, has been conducted. Full autorotation landings, however, was performed as safety precaution and for crew training before starting the autorotation entry testing. It was possible to perform all testing involving engine failure simulation or autorotation at safe height above terrain, since there was no requirement to demonstrate full autorotation landing starting from specific height/speed points, as for the case where the full H–V curve is demonstrated.

For the particular installation, it was estimated that less than 30 test points were necessary to investigate and demonstrate the H–V diagram, as opposed to the foreseen 80 + test points necessary for a complete investigation of the H–V curve [14].

7 Conclusions

The proposed alternative approach on H–V testing, based on the use of a preliminary phenomenological investigation, allows STC applicants for external installations to drive down the costs of flight testing without reducing safety margins.

Considering that the H–V diagram may represent the limiting capabilities of the rotorcraft, the method consists in dividing the autorotational landing maneuver, following an engine failure, into four characteristic phases and conducting, for each phase, a back-to-back quantitative comparison of the key performance parameters, between the unmodified (baseline) and modified configuration.

In case no substantial differences are detected between the configurations, it can be concluded that the helicopter capabilities in performing a safe autorotation landing are not impaired by the modification and the success of the maneuver depends basically on the Pilot's ability to select the optimal control strategy. In this case, the alternative proposed method is highly beneficial as it brings major benefits. In particular:

- no complete engine-out landing must been conducted on the edge of the H–V curve or in its proximity;
- engine failure simulation or autorotation tests can be conducted at safe height above terrain;
- the test method does not require testing at a high-altitude site to be performed, which is often impractical or excessively expensive for a Design Organization, requesting an STC certification, without being the TC Holder.

In case differences are detected in the back-to-back comparison of the key performance parameters, the proposed method cannot be considered definitive in demonstrating compliance to CS 27/29.79 and H–V testing must be reintroduced and performed as required by the Certification Memorandum [2]. The results of the proposed method used as a preliminary investigation, however, could be used to mitigate the risk associated to the actual H–V

curve investigation, as only the affected and relevant parts of the H–V curve would require to be verified with actual flight test data.

To conclude, the proposed method can offer a valid and practicable quantitative alternative to the actual investigation of the H–V curve, which involves high-risk maneuvers, difficult to perform in a consistent and repeatable way.

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