ENGINE BACK-UP SYSTEM IN FLIGHT TEST CAMPAIGNS: A NEW APPROACH TO THE HEIGHT-VELOCITY DIAGRAM DEMONSTRATION

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Abstract

The Height-Velocity (H/V) diagram is one of the key stages in the Maximum Take-Off Weight (MTOW) demonstration during the certification of a new helicopter or in the event of an increase in mass of an existing helicopter. The recent development of hybrid propulsion solutions allows for the implementation of an electric engine back-up system (EBS). In case of thermal engine failure, this electric power assistance could change the paradigm. Between July 2021 and May 2022, Airbus Helicopters carried out an extensive flight test campaign on the H130 Flightlab presented in this paper. The EBS installed in the Flightlab provides electrical assistance of about 100kW in case of engine failure. Preliminary studies had shown that it could allow a MTOW increase close to 200kg without an H/V diagram modification on the H130 helicopter type. To avoid flying above the certified MTOW on the Flightlab prototype, Airbus Helicopters used the H130 performance model to convert the 200kg target of mass increase to a H/V diagram area reduction, thus minimizing the applied stress constraint during that campaign. Moreover, battery autonomy and time of charge limited the training of the flight test crew and the gradual approach to these critical points. Airbus Helicopters adapted the thermal engine software to simulate the EBS assistance. The analysis of the flight test results has demonstrated the validity of the mass to the H/V diagram reduction equivalence, successfully mitigating the risk in approach during the flight test procedure. Thanks to this process, Airbus Helicopters is now actively taking into consideration an H130 MTOW extension with a hybrid propulsion system for an upcoming certification, the first of its kind in the helicopter industry.

1. NOTATIONS

CG	Center of Gravity
EBS	Engine Back-up System
FADEC	Full Authority Digital Engine Control
IGE	In Ground Effect
ISA	International Std Atmosphere
HMI	Human Machine Interface
H/V	Height-Velocity (diagram)
MTOW	Maximum Take-Off Weight
M_σ	Reduced Mass
NR	Rotor Revolutions per Minute
N_Z	Vertical Load Factor
OAT	Outside Air Temperature
OGE	Out of Ground Effect
rpm	Revolutions Per Minute
TAC	Technical Advice Contract
Z_σ	Density Altitude
Z_P	Pressure Altitude

2. INTRODUCTION

The height-velocity (H/V) diagram is one of the key stages in the Maximum Take-Off Weight demonstration during the certification of a new helicopter[1], [2]. In the event of an increase in mass of an existing civilian helicopter, the H/V diagram demonstration has to be carried out at the new gross weight to show compliance with CS27[3] applicable standards for takeoff (§ 51), landing (§ 75) and height / speed envelope (§ 79) for small rotorcraft or CS29[4] height / speed envelope (§ 87) for large rotorcraft. A flight test demonstration of the H/V covers the landing procedures in case of engine failure all along the

H/V diagram border. During this flight test campaign, we focused on the three key points of the H/V diagram: high hover, knee, and low hover points. In the past, the helicopter mass extensions could result in an unacceptable size of an H/V area, which became a limiting factor in the maximum weight certification, in particular for single engine helicopters. The recent development of hybrid propulsion solutions allows for the implementation of an electric engine back-up system (EBS). In case of thermal engine failure, this electric power assistance could change the paradigm.

3. H/V DIAGRAM DEMONSTRATION

To be compliant with CS27, the H/V diagram must be demonstrated at MTOW from standard sea-level conditions to the maximum altitude capability of the rotorcraft or Z_σ = 7000ft whichever less, and include simulated engine failures on:
- Low hover point (with no time delay other than normal pilot reaction time)
- High hover point (with 1 sec delay)
- Knee point in level flight (with 1 sec delay)
- Knee point in takeoff configuration (with no time delay other than normal pilot reaction time)

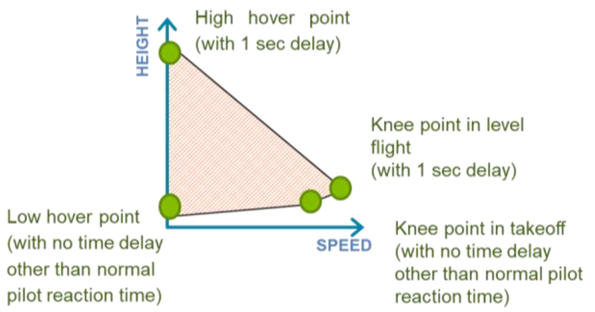

Figure 1: Height-Velocity Diagram Demonstration

For example, let us consider the MTOW extension of the H130T2 at 2500kg[5] from the original H130B4, which had initially a MTOW of 2427kg[6]. This MTOW extension was possible due to an increase of maximum takeoff power. This example is particularly relevant as the Flightlab prototype is an H130T2 helicopter type. The H/V diagram was demonstrated in high altitude conditions in 2012 in Ruidoso / USA – New Mexico. During the test point of engine failure in takeoff path at 2571kg, Z_p = 6407ft OAT = - 4°C, the landing was well controlled but with a high rate of descent and therefore a high N_Z load factor at touchdown. Even though the test point was judged acceptable, no further tests were performed in high altitude for the H/V diagram. The H130T2 final performance results were hence derived from the existing campaign carried out in Albuquerque in October 2000, for the original H130B4 certification. That campaign of October 2000 showed that the critical point was in the following conditions:

- Knee point in level flight (100ft / 65kts with 1 sec delay) with M = 2408kg; M_σ = 3045kg; Z_p = 5697ft; OAT = 22°C; Z_σ = 7804ft.

Therefore, these tests were not performed again at 2500kg for H130T2 mass extension but they have been used to show compliance with the requirements, considering an appropriate flight envelope limitation in terms of reduced mass. This approach limited the MTOW of the H130T2. In practice, this reduced mass has become a limiting parameter above Z_σ = 6600ft up to Z_σ = 7000ft. This limitation is mentioned in the H130T2 Flight Manual[5] as observed in Figure 2.

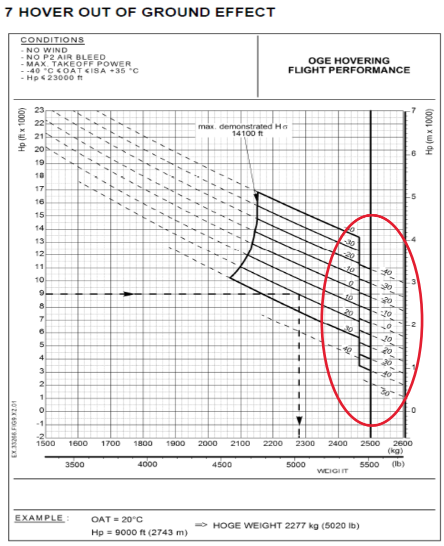

Figure 2: Extract of H130T2 Flight Manual: OGE Limitation due to H/V Diagram Demonstration

To conclude, the H/V demonstration became a limiting factor in MTOW certification of the H130T2.

4. ENGINE BACK UP SYSTEM : NEW APPROACH TO H/V DIAGRAM

The recent development of hybrid propulsion solutions allows for the implementation of an engine back-up system (EBS) that changes the game. Initial work on the use of an EBS started 10 years ago[7], [8]. Since then, improvement in energy density of the batteries has led to significant EBS weight and volume reduction. Today, the benefit of power from the EBS compared to its mass is sufficiently interesting[9]. The EBS provides electrical power to the main gearbox and the main rotor in case of thermal engine failure. The system is composed of five main components described in Figure 3.

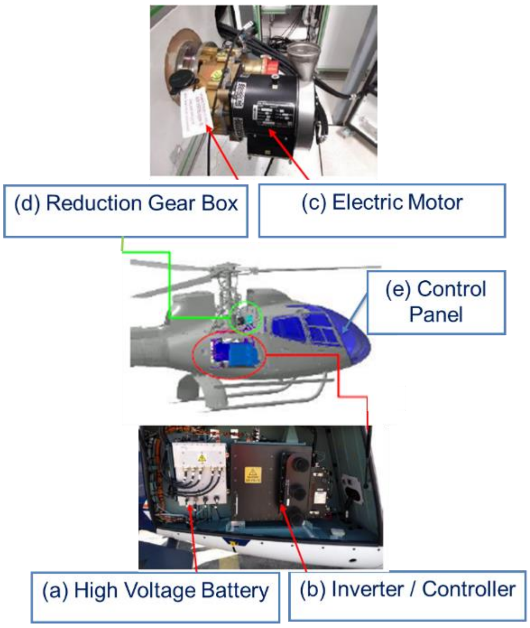

Figure 3: The EBS Main Components

This includes the electric storage unit: a high voltage Lithium-Battery (a) as well as inverter and controller to convert the High Voltage (HV) Direct Current (DC) into High Voltage Alternate Current (AC) (b). The electric motor (c) is connected to the main gearbox thanks to a dedicated reduction gearbox (d). A NR sensor and associated phonic wheel are introduced in the gearbox assembly to allow the automatic activation / deactivation of the back-up system in case of thermal engine failure. A freewheel disconnects the emergency electric engine from the rest of the drive system in nominal condition and connects it in engine back-up mode. Finally, a dedicated control panel (e) is installed in the cockpit to control the EBS as well as alert the crew to its state for the flight test campaign.

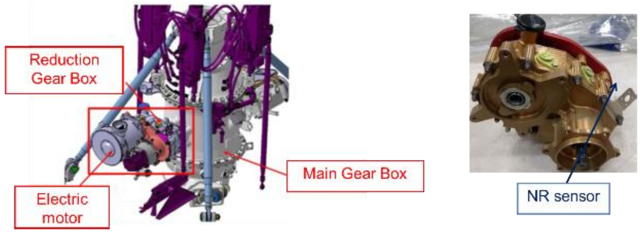

Figure 4: Reduction Gearbox with NR Sensor Interface

Electric Motor Characteristics	Values (indicative)
Type	Brushless permanent magnet
Power	100 kW during 30sec
Efficiency	95 %
Cooling	External air with duct
Nominal speed range at rated power	~ 25 000 rpm
Weight	~ 12 kg

Table 1 : Main Characteristics of the Electric Engine

The EBS increases performance and safety, especially for single-engine helicopters, since the prompt electrical power injection will limit the rotor speed drop when a thermal engine failure occurs. In the event of an engine failure, pilots can adjust their rate of descent by injecting electrical power as needed by the rotor speed datum targeted. EBS also provides a safer and softer touch down at the end of the autorotation. Thanks to the additional power available to the pilot as well as the reactiveness of the electric engine, it allows more time to react and more time to choose the safest landing area around, than in a classical autorotation.

The activation and deactivation criteria have been tuned during the flight test campaign to find the best compromise between prompt activation of the emergency system and inadvertent activation in case of dynamic maneuvers in flight. The laws are the following:

EBS activation criterion: $f_{n_A}(NR) < NR_A$

EBS deactivation criterion: $f_{n_D}(NR) > NR_D$

The Figure 5 below schematically describes these principles.

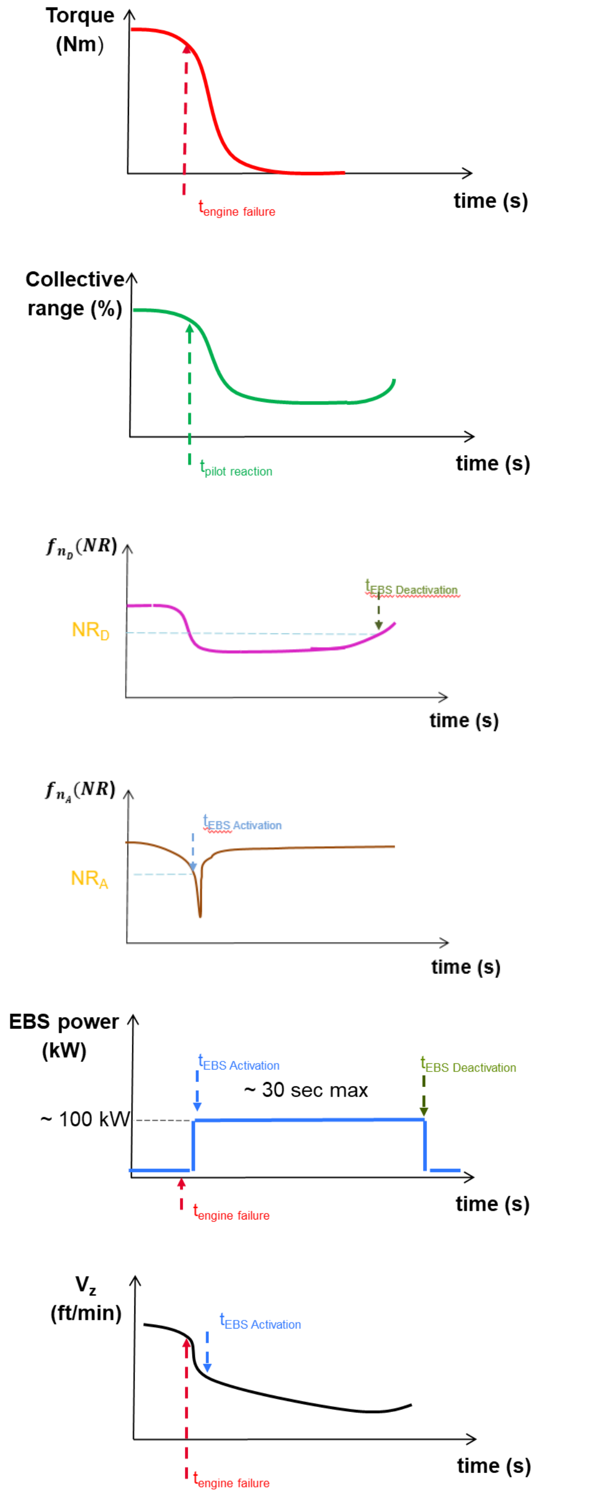

Figure 5: The EBS Principles of Activation and Deactivation

Indeed, once the thermal engine failure occurs, the torque decreases drastically. Briefly after that event, the pilot is trained to reduce his collective level to control the NR drop. If the function of the NR drops below a specific NR_A value, then the EBS is activated. It delivers about 100kW during 30 sec or less if the NR rises above the NR_D value. That additional electrical power reduces the high rate of descent and therefore minimizes the N_Z load factor at touchdown.

5. EFFECT OF EBS ON MTOW INCREASE

Flightlab is the Airbus flying test bed fully dedicated to testing different research techno-bricks shaping the future of helicopters. It is an H130T2 single-engine helicopter type which can accommodate a pilot plus up to 7 passengers. The EBS installed in the H130T2 Flightlab provides electrical assistance of about 100kW during 30 seconds in case of thermal engine failure. Before the flight test campaign, preliminary studies done by the design office had shown that it could allow a MTOW increase close to 200kg[10] without an H/V diagram modification on the H130T2. Considering the EBS's own weight, it is therefore possible to expect an extra payload of about one additional passenger.

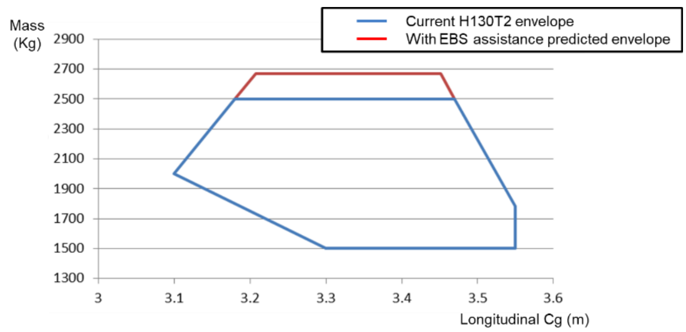

Figure 6: Current and Foreseen H130T2 Weight & CG envelope with EBS

6. H130 MODEL PERFORMANCE: MTOW VERSUS H/V DIAGRAM

To avoid flying above the certified MTOW on the Flightlab prototype, the design office used a performance simulation model to convert this 200kg target of mass increase to a H/V diagram area reduction. The aim of that strategy was to minimize the applied stress constraint on the prototype during the flight test campaign. It has also facilitated the airworthiness analysis and thus made it easier to get the permit to fly. The simulation used an unsteady performance tool based on energy method. The piloting was optimized during the simulation replay to minimize vertical speed at impact. More precisely, there is no direct conversion from mass increase to H/V diagram area. That is why, as described in the next paragraph, a part of the purpose of flight test campaign has been to validate the representativeness of the H130T2 performance model at sea level ISA and MTOW for maneuvers like the one in the H/V demonstration, with and without the EBS assistance.

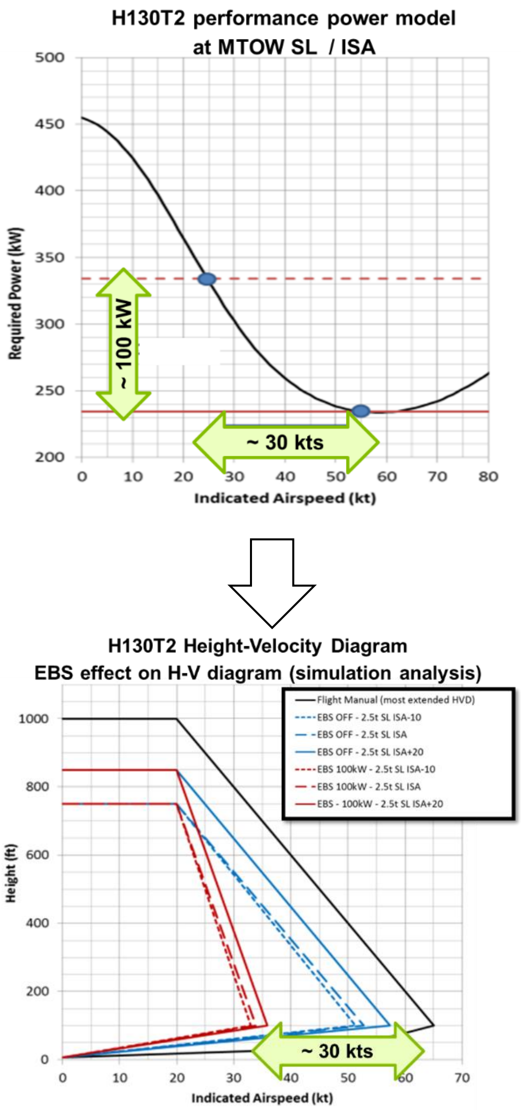

Figure 7: Simulation Results on the Effect of EBS Additional Power on MTOW vs H/V Diagram Area Reduction

7. FLIGHT TEST CAMPAIGN CHALLENGES

Between July 2021 and May 2022, Airbus carried out an extensive flight test campaign on the H130 Flightlab equipped with the EBS. The purpose has been to accurately assess the safety and performance benefits of such a device. In total, 3 ground runs and 9 flights with 3 fully dedicated to the H/V diagram demonstration have been completed. The total time was 11h including 6 flight hours for H/V demonstration with the following distribution:

- 16 test points without EBS or adapted thermal engine software of EBS assistance
- 24 test points with adapted thermal engine software of EBS assistance
- 17 test points with EBS

Figure 8 : View of the Inverter and the High Voltage Battery in the Right-Hand Cargo Bay of H130 Flightlab

Figure 9: The H/V Demonstration of H130 Flightlab during the EBS Test Campaign

The engine failures were simulated during the key points of the H/V diagram by setting the engine to idle. The maneuvers covered landing after thermal engine failure. The engine power variation had to be representative of a real engine failure. To do so, a specific FADEC software has been used for the test campaign. The software version included the following features: a quicker transition between flight and idle and a minimal idle power representative of the thermal engine failure. That kind of software adaptation has been used in the past for H/V certification. During this flight test campaign, 16 points have been thus performed to revalidate the initial H130T2 performance model at sea level ISA and MTOW for maneuvers such as those in the H/V demonstration.

However, one of the main challenges of this flight test campaign was linked to the autonomy of the batteries and their time of charge. Indeed, these constraints would have limited the training of the flight test crew and the gradual approach to the H/V critical points with EBS assistance. To alleviate that risk, preliminary flight tests points have been done with another adapted thermal engine software to simulate the EBS assistance. This software also included a quicker transition between flight and idle and especially an idle power corresponding to around 90kW to simulate EBS power input. It allows a quicker approach to critical test points, without using the batteries. Therefore, this innovative flight test strategy minimized the cost and the time of the flight test campaign. But above all, it improved the safety and the confidence of the flight test crew thanks to adequate training and a gradual approach to the critical points before using the EBS itself.

To conclude, this approach with adapted FADEC software for EBS made it possible to validate the hybrid helicopter performance model as well as familiarize the flight test crew with the test beforehand without the actual electric assistance. In the end, this method maximized safety while minimizing the overall cost and time of the flight test campaign.

8. FLIGHT TEST CAMPAIGN RESULTS

Once preliminary tests with simulated residual thermal engine power on Flightlab had validated the performance model and the hybrid performance model, the H/V diagram points were performed without and with the EBS assistance, at 2.5 tons (MTOW of H130T2). The flight test results of this campaign have shown a significant decrease of the «Dead Man's» zone of the H/V diagram:

- knee point (takeoff and level flight merged) : without the EBS 65kts/100ft vs. with the EBS 40kts/100ft
- low hover: +3ft with the EBS assistance
- high hover: -350ft with the EBS assistance

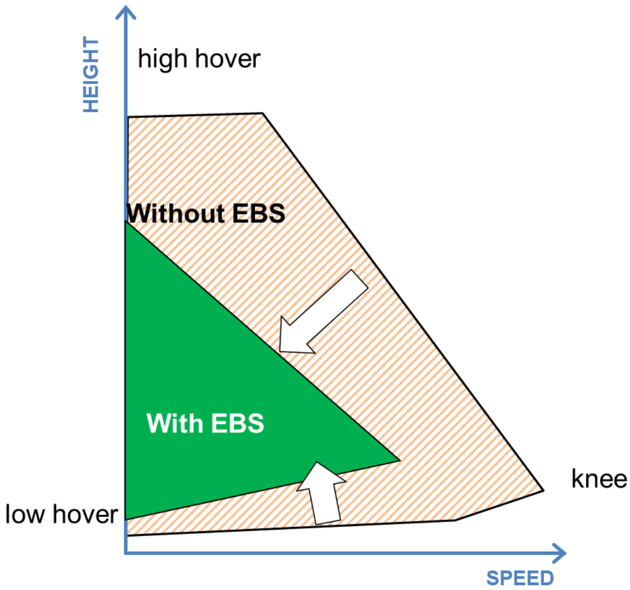

Figure 10: The H/V Diagram Reduction Thanks to EBS Based on the H130 Flightlab Campaign Results

The H/V diagram was performed by the flight test crew, trying to maintain, for the same maneuvers, an equivalent level of piloting difficulty as the one in the initial H130 certification campaign.

Figure 11 is a recording of the actual high hover test point at MTOW, comparing the flight parameters in **EBS OFF** vs **EBS ON** curves.

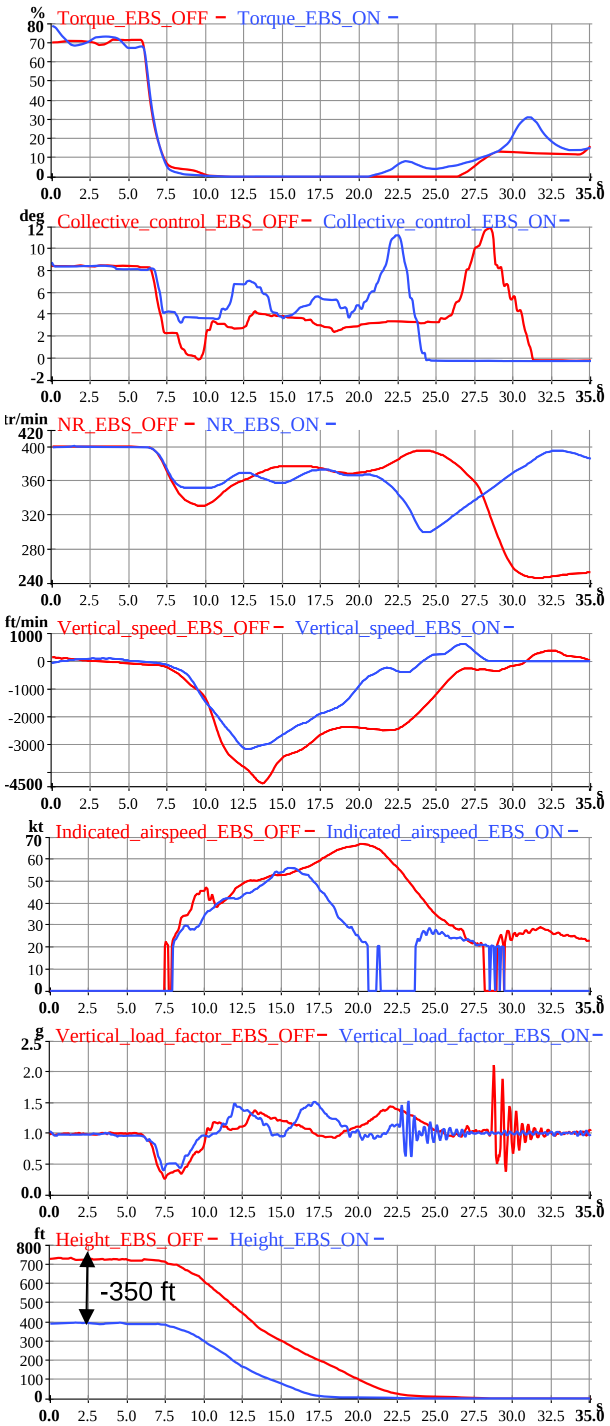

Figure 11 : Recording of the Actual High Hover Test Point at MTOW, EBS OFF vs EBS ON

On the torque curve, we can see that the engine failure occurred at about t = 5 sec. The collective level is decreased by the pilot. However, with the **EBS ON**, the collective is maintained at a higher level than on the **EBS OFF** curve to keep the current NR below the EBS NR deactivation value NR_D. That piloting strategy optimizes the EBS assistance to get a lower vertical speed and a lower indicated speed at the approach, resulting in a lesser load factor at landing. As a result, there is on the height curve an improvement of - 350ft for the high height hover H/V diagram point.

The flight test campaign has allowed for adjusting the modeling of EBS in simulations. The analysis of results confirmed the estimated gains given by simulation in term of H/V area reduction and the autorotation performance enhancement. Therefore, it has demonstrated the validity of the performance model for H/V maneuvers with and without EBS. It helped to confirm the mass to the H/V reduction equivalence, successfully mitigating the risk in approach during the flight test procedure. Ultimately, the design office validated by simulation that an EBS at 100kW is sufficient for the MTOW target increase of about 200kg, which, considering the weight of the EBS, could provide a helicopter operator with an additional payload of about one passenger. That risk mitigation has been possible without actually flying above the certified MTOW on the Flightlab prototype. The adapted FADEC software, that Airbus asked the engine manufacturer to develop, allowed for adequate training and a gradual approach to the critical points. Furthermore, the flight test crew established during the campaign an optimized piloting strategy when using EBS. Indeed, as seen in the high hover point example in Figure 11, the pilot should obviously decrease his collective level when the thermal engine failure occurs, as on a classical single engine helicopter. But, to keep the EBS assistance, his collective should be maintained at a higher level to have the NR below the EBS NR deactivation value NR_D. That technique of piloting is similar to a twin-engine helicopter and indeed needs an adequate HMI interface for a future serial application.

In case of engine failure far from ground, pilots could not use electrical assistance all along autorotation descent. However, at the time the failure occurs, EBS will limit the NR drop and thus the pilot workload. When NR is controlled, usual autorotation is established at Vy (70kts on the H130) and NR maintained above NR_D to save battery power. At a height of around 300ft, collective is increased to take benefit from the EBS assistance to reduce vertical and forward speed before flare. Flare will so be initiated, with the EBS, at a lower vertical speed (800ft/mn compared to 1800ft/mn) and lower forward speed (40kts compared to 70kts). During the flare EBS will continue to help the pilot for touchdown. The result is a touchdown at lower Nz, lower forward speed with the EBS, minimizing the subsequent slide length.

9. FUTURE WORK

Thanks to this innovative testing strategy, Airbus is now actively taking into consideration an H130T2 MTOW extension with a hybrid propulsion system for an upcoming certification. Work with EASA is ongoing, focusing on EBS and, in particular, on the thermal runaway testing of high voltage batteries, crashworthiness and the certification perimeter of the H130 MTOW increase. A Technical Advice Contract (TAC) has been assessed by EASA to define areas of novelty and associated certification challenges for the installation of an EBS in the H130T2. The report mainly covers high voltage battery installation, emergency electric engine, and reduction gearbox. EASA listed there the references [11], [12], [13], [14] and [15] to make the H130T2 certification basis adequate to a design change for the EBS installation. Anticipation of certification aspects with EASA since 2019 has now made possible for Airbus to consider certifying and manufacturing this hybrid engine solution, the first of its kind in the helicopter industry.

For a serial application, a dedicated HMI for EBS should be developed to inform the crew of the state of the EBS and help optimize the piloting technique though the adequate collective level and associated NR. Furthermore, pilots should be adequately informed and mechanics trained to the specificities of EBS.

Eventually, for a serial application, the battery could be recharged using the thermal engine during flight. EBS current design is already capable of providing this function even though it has not been implemented yet.

In the future, EBS could address the issue of the strict rules of flying over cities. Indeed, a single-engine helicopter must be able at every moment, in case of an engine failure, to land outside of a city, or its flight path must ensure that it is able to land on areas without danger for people on the ground. An upgraded EBS version will also be able to alleviate this constraint. Moreover, the main sources of helicopter noise are its rotor and engine. In the future, this upgraded version, with its capability of quickly providing power thanks to the responsiveness of an electric motor, could allow for a significant reduction of NR in cruise. This will permit quieter operations.

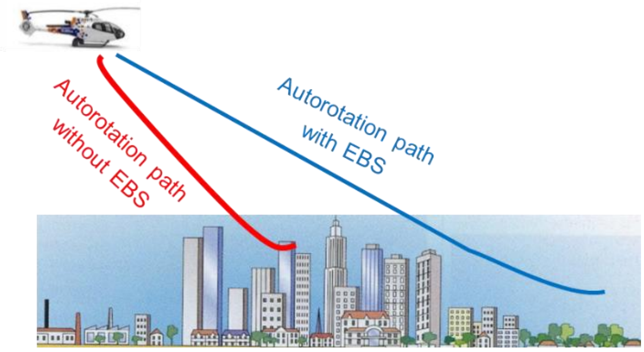

Figure 12 : An Upgraded EBS Version Could Alleviate the Strict Rules of Flying over Cities for Single-Engine Helicopters

Long term, one could imagine an advanced hybrid implementation with the use of the electric motor throughout a helicopter mission profile. The EBS would be used not only during emergency phases but also, for example, for hover, takeoff or go around - which are the most power consuming phases. The thermal engine design could be adapted only for the cruise and landing, and the electric back-up motor available for the other high power consuming phases. The benefits of such a design are obvious for passenger safety, but also significant in terms of fuel consumption and noise reduction. In the future, one can also imagine EBS installed on twin engine helicopters where the second engine would be put on idle during the cruise and the electric engine available for high power consumption phases or emergency.

10. CONCLUSION

As we described in this paper the H/V diagram has always been a critical flight test demonstration, mostly on single engine helicopters. For the Flightlab, which is an

H130T2, the H/V diagram was in fact a limiting factor in the maximum weight certification. Between July 2021 and May 2022, Airbus Helicopters carried out an extensive flight test campaign on the Flightlab prototype to assess the safety and performance benefits of an electric back-up system.

An innovative flight test strategy was defined to successfully manage this flight test campaign. Firstly, the target of MTOW increase was converted in H/V area reduction by simulation. The campaign results adjusted and validated the simulation performance model for H/V maneuvers with and without EBS. Consequently, they helped to confirm the mass to H/V reduction equivalence, successfully mitigating the risk of a future MTOW extension on the H130T2. Eventually, the design office validated by simulation that an EBS at 100kW is sufficient for the MTOW target increase of about 200kg. Considering the EBS weight, this could offer a helicopter operator an additional payload of about one passenger. In addition to the MTOW increase, the EBS installation improves safety in case of engine failure since the electrical power injection will limit the rotor speed drop when the failure occurs. It also provides a safer and softer touch down at the end of the autorotation procedure. Moreover, by giving 30 seconds to the pilot, EBS allows more time to react and more time to choose the safest landing area around.

The use of adapted thermal engine software to simulate the EBS assistance has minimized the cost, the time, and most of all increased the safety of the flight test campaign. Indeed, it has allowed an adequate training of the flight test crew and a gradual approach to the critical H/V points, which would have been impossible with the autonomy of the battery and its time of charge.

Furthermore, the flight test crew developed an enhanced piloting strategy when using EBS. To keep the optimal EBS assistance, the collective should be maintained at a higher level than on a conventional single engine helicopter so that the NR stays below the EBS NR deactivation value NR_D. This piloting technique is similar on a twin-engine helicopter and needs an adequate HMI interface for a future serial application.

On top of the safety and performance improvements that EBS has proved to bring, it constitutes a first reliable step towards the hybridization of helicopter propulsion with electrical energy. The Flightlab flight test results and associated innovative strategies should therefore also be regarded as a major milestone in the journey towards sustainable aviation.

To conclude, this successful flight test campaign has shown that flight testing is an ever-changing world. New technologies need new ways of testing. These innovative means have been developed by Airbus on the foundation of more than 70 years of history and experience in the flight test area.

11. REFERENCES

[1] G. Leishman, “Principles of Helicopter Aerodynamics”. Cambridge University Press, 2nd ed., 2006

[2] R. Prouty, “Helicopter Performance, Stability and Control”. Florida Kriger Publishing Company, 1st ed., 1989

[3] Certification Specifications, Acceptable Means of Compliance and Guidance Material for Small Rotorcraft CS-27, European Union Aviation Safety Agency, Amdt. 9, 2021.

[4] Certification Specifications, Acceptable Means of Compliance and Guidance Material for Large Rotorcraft CS-29, European Union Aviation Safety Agency, Amdt. 10, 2022.

[5] H130T2 Flight Manual, European Aviation Safety Agency, 2022.

[6] EC 130 B4 Flight Manual, European Aviation Safety Agency, 2000.

[7] Matthieu Connaulte, Christian Mercier, Damien Mariotto: “Method of assisting a pilot of a single-engined rotary wing aircraft during a stage of flight in autorotation”. Patent, 2015

[8] Marie-Laure Hopdjanian, Matthieu Connaulte, Marc Gazzino, Christian Mercier: “Electrical architecture for a rotary wing aircraft with a hybrid power plant”. Patent, 2014

[9] T. Krysinski, F. Malburet: “Energy and Motorization in the Automotive and Aeronautics Industries”. Willey, 2020

[10] B. Benoit, A.M. Dequin, K. Kampa, W.v. Grünhagen, P.M. Basset, B. Gimonet: “HOST: A General Helicopter Simulation Tool for Germany and France”, American Helicopter Society,56th Annual Forum, Virginia Beach, Virginia,May 2000.

[11] Final Special Condition SC E-19 - Electric / Hybrid Propulsion System, European Aviation Safety Agency, SC E-19 Issue 01, 2021

[12] Special condition Non-rechargeable Lithium Battery Installations, European Aviation Safety Agency, 2021

[13] Eurocae ED-289 “Guidance on the determination of accessible energy in battery systems for eVTOL applications”

[14] Eurocae ED-290 “Guidance on High Voltage Definition and Consideration for Personal Safety”

[15] Eurocae ED-296 “Design Assurance Guidance for High Voltage Standards and Power Quality for VTOL applications”