LIGHTNING THREAT ON VTOLS

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Abstract

Lightning zoning is the basis to define the lightning threat at rotorcraft and components/equipment level, for protecting the rotorcraft against both direct and indirect effects of the lightning.
For conventional Rotorcraft and Aircraft, the lightning zoning certification guide (ED-91A) was recently updated considering extensive in-service lightning event background of Rotorcraft and Aircraft manufacturers. The evolutions are described in this paper.
However, these generic lightning zonings cannot be used directly for new platforms as VTOL with non-conventional shapes. At this end, a new method for developing lightning zoning is proposed by EUROCAE WG112 which is based on a so called Mix and Match (M&M) method, processing a similarity with generic Rotorcraft and Aircraft zonings as per ED91 A.
The paper shows that this method can be complemented by using lightning zoning simulation tools in the purpose of supporting the complete lightning safety analysis, with providing the set of lightning scenarios relevant for showing the compliance to lightning certification requirements and therefore enhancing the assurance level provided by the demonstration process.
For allowing the use of these simulation tools as a support for defining the lightning compliance demonstration strategy, the consistency between both simulation results and experience is shown on a conventional helicopter in this paper. First zoning calculations are provided on a first VTOL use case.

1. INTRODUCTION

To define the lightning threat on Airbus Rotorcraft and to define lightning scenario for the certification, document ED-91A “Aircraft Lightning zoning” [1] is used.

This document was prepared by EUROCAE Working Group 31 “Lightning” and was approved by the Council of EUROCAE on 04 January 2019. It supersedes ED-91 “Aircraft Lightning Zoning”, July 1998 and it is technically identical to SAE ARP5414B. Coordination has been achieved with SAE AE-2.

This EUROCAE ED / SAE Aerospace Recommended Practice (ARP) defines lightning strike zones and provides guidelines for locating them on particular aircraft, together with examples. The zone definitions and location guidelines described herein are applicable to Parts 23, 25, 27, and 29 aircraft. The zone location guidelines and examples are representative of in-flight lightning exposures.

Lightning zoning is a fundamental step for determining appropriate lightning protection for the Rotorcraft, and also for defining the strategy for verifying the lightning indirect effect compliance as illustrated in the ED113 [13] flow chart.
Lightning tends to attach to and sweep across specific locations on aircraft. This document provides definitions for regions of aircraft where lightning attachments are likely and where lightning attachments are expected to sweep. These lightning attachment regions or zones can be used to define appropriate lightning protection for structure systems, along with certain aspects of the fuel system. These zones can be used to define appropriate tests to demonstrate that the lightning protection is effective.

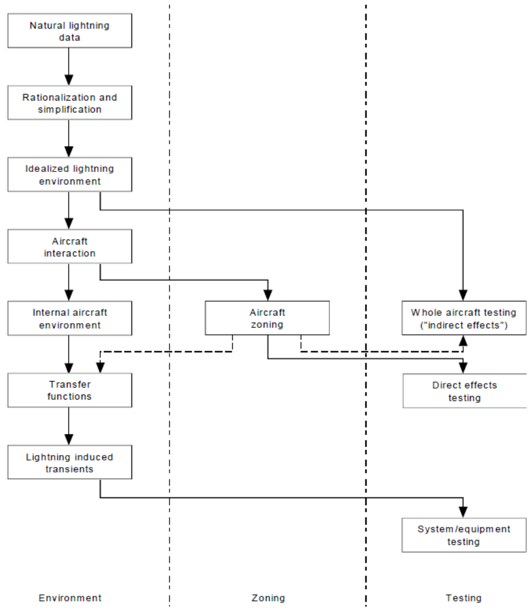


Figure 1: Relationship between aircraft environment, zoning and testing (ED113)

The helicopter lightning interaction can be divided in 3 processes:
- Zone 1: Initial lightning attachment: this is mainly the case of the extremities as the tip of the blades or the landing gear.
- Zone 2: Swept channel process: this is for example the case of the bottom of the airframe due to the motion of the H/C or the main airfoil of the blades due to the rotation of the blades
- Zone 3: And conduction process associated to conduction zones, with low probability of impact. This is the case of the part of the airframe protected by the rotor which attract preferentially the lightning channel.

The locations of the lightning strike zones on any aircraft are dependent on the geometry of the aircraft and operational factors. If a new/modified aircraft is similar to an existing aircraft whose zoning has been validated by service history, the new/modified aircraft can be zoned in the same manner as the existing aircraft. For aircraft that are of new or novel design (or for areas of an aircraft that incorporate new or novel design), a specific location process is to be applied to determine the lightning zones.

2. EXPERIENCE IN SERVICE

Data about in service incidents due to lightning strikes are collected from customer's supports, so that a continuous follow-up of in-flight incidents is performed and data are compiled in a specific database containing:

- General data of the incidents (H/C Number, meteorological data, location of the lightning strike, particular events noticed by the crew),
- Information about the damage obtained (including equipment failures)

The Tables 1 and 2 are providing detailed data.

Table 1: Airbus H/Cs Struck by Lightning (from 1976 to 2022)

H/C Type	Number of H/C struck	Number of H/C struck in North Sea
Super Puma	77 (64 MK1 & 10 MK2 & 3 EC225)	59 (47 MK1 & 10 MK2 & 2 EC225)
BO105	1	0
BK117 – EC/H145 H135	8 1	0
Ecureuil/A-STAR	19	/
Dolphin	11 (1 AS366GA)	2 (AS365)
Puma	9	/
Gazelle	1	/
H120	3	/
NH90	1	/
Total	131	61

Remarks: Data from North Sea are highlighted since about half of the events occurred in this area.

20 H/C were struck on the ground.

Table 2: Items Damaged by Lightning Strike (from 1976 to 2021)

Items		Number
Blades	Main Rotor Blade	233
	Tail Rotor Blade	54
Equipment		45
Structure	Landing Gear	12 (2 in flight)
	Tip of Tail Fin	6
	Horizontal Stabilizer	9
	Dischargers (tail)	2
	Fuselage (bottom part)	1
	Tail Skid	3
	Radome	1

Remark: Exposed parts observed through H/Cs struck in service, are in line with exposed parts identified though the typical zoning provided in documents ED-91/ARP-5414.

Rotors and blades in particular, are the items the most frequently damaged, due to their exposure, shape, nature of materials (conductive: metal, carbon).

Damage on the airframe and radome is much less frequent than on rotors. The other damaged areas correspond mainly to protuberances of the rotorcraft, as in rear parts with tip of horizontal stabilizers, tip of tail fin, tail skids

Considering the classification in zone 2A of the main airfoil and root of the blades, even if the phenomenon of sweeping seems natural to be taken into account on rotors (around 4 rev/s for the main and 20 rev./s for the tail), the level of 100 KA is much more severe than what is noted in terms of damage in service, so the question of a change could be legitimate, either an adaptation of the peak of zone 2A but that needs new characterizations of the threat and changes in standard document (ED-84), or a change of classification of the main airfoil of blades, the possibility being a zone 3N (40 KA); in this last case, the purpose would be to focus on the associated peak level rather than on the mode of interaction (zone 2 deals with sweeping, while zone 3N deals with attachment).

For information in the new documents ARP5414B/ED91A the experience of 3 helicopter manufacturers including AH (letter X) is reported in Table 3.

Table 3: Lightning Strike data from rotorcraft manufacturers in ARP5414B/ED-91A

Rotorcraft Manufacturer	Lightning Strike Reports	Main Rotor Blades	Tail Rotor Blades	Tail Fin	Horizontal Stabilizer	Hoist or Cargo Line	Landing Gear	Stinger	Nose	Belly
X	122	106	24	3	8	0	1	3	1†	0
Y	44	29	6	1	5	3	0	2	0	0
Z	52	52	47	1	6	0	0	0	0	1*
Total	218	187	77	5	19	3	1	5	1†	1*

† Old data with just one line referring to light radome damage.

* Rotorcraft with retractable undercarriage and V-shaped lower boat hull.

Manufacturer X (AH) included data (end 2018) taken over approximately 40 years with strike frequency of approximately 1.4 x 10-6 per flight hour, but this depends strongly on helicopter utilization. The data includes 17 strikes that occurred on the ground. The total number of struck blades includes 225 main blades and 54 tail blades. Manufacturer Y had 70 lightning strikes reported between 1981 and 2014, of which 26 were reported as on the ground and so excluded from the table, and 12 for which no damage details are available. Total flight hours are not available.

Manufacturer Z had 52 in-flight lightning strikes reported. Strike frequency rates depend on operations.

The majority of reported lightning strike attachments are to the main and tail rotor blades, in many cases attaching to more than one blade. Some strikes have also been reported to the tail fin, horizontal stabilizers and the stinger on the lower trailing surface of the tail boom. The percentage of rotorcraft strikes reported as occurring to the nose is less than 0.5%. The percentage of rotorcraft strikes reported as occurring to the belly is less than 0.5%.

Remark: The data for AH (letter X) are not exactly the same as in table 3 since data in table 3 are more recent and include the last lightning events).

The new zoning is consequently in line with the experience in service.

3. LIGHTNING ZONING

Indeed, from 2014 to 2018, the regulatory working groups SAE-AE-2 and EUROCAE WG31 have reviewed the lightning zoning document. Concerning the rotorcraft, this new zoning, with an initial proposal of Airbus was discussed by five helicopter manufacturers (Bell, Robinson H/C, Sikorsky, Leonardo & Airbus) and is mainly based on in-flight experience.

The main modifications are the suppression of lightning zones 2 (sweeping zone) of the airframe and of zones 1 on the nose.

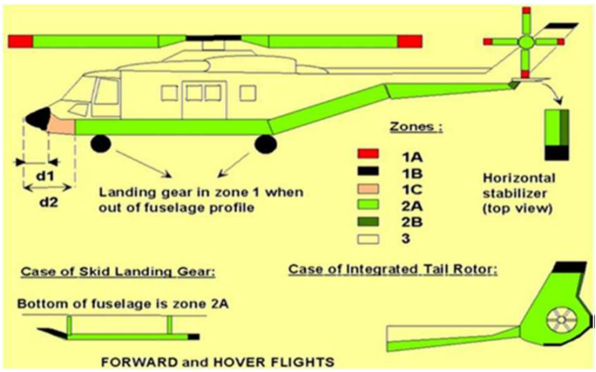


Figure 2 : Previous lightning zoning (ED91)

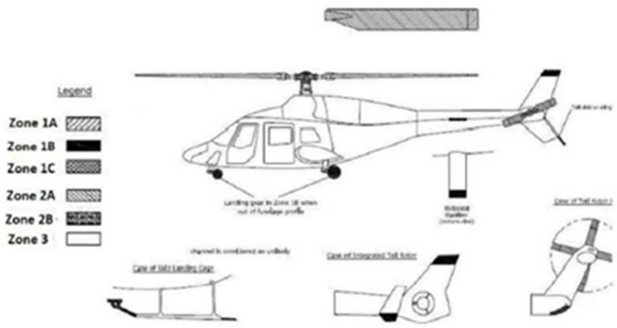


Figure 3: New lightning zoning (ED91A)

The airframe will be consequently mainly in zone 3 where any primary attachment or sweeping of the lightning channel is considered unlikely, but emphasizes the role of the protrusions which may modify locally the zoning with possibly risk of attachment.

4. SPECIFICITIES OF VTOL

A direct similarity is obviously inappropriate for unconventional platforms called Vertical Take-Off and Landing aircraft (VTOL) with new aeromechanical configurations as multi-engines platforms, e.g. City Airbus and Vahana. But a mixed similarity as proposed by EUROCAE WG112 mandated for developing lightning zoning guidance is on purpose, using the extensive flight experience of conventional Rotorcraft and Aircraft. This similarity method mixing both the Rotorcraft and the Aircraft lightning zoning depending on the VTOL part is supposed to provide a “worst case” zoning what is positive for the safety, but since a reasonable worst case avoiding overdesign of the lightning protection. This approach is also fully relevant for any non-conventional platform as the Airbus high-speed demonstrator, the Racer.

igure 4: Racer

Figure 5: CityAirbus NextGen

Considering that the lightning zoning will be develop according to the guidance developed by the WG112, the following section shows that this zoning established by similarity can be complemented by calculations for supporting the overall lightning zoning analysis. Two models are presented and applied for the computation of the primary attachment zones of a conventional H/C. The simulation results are validated by showing consistency with generic zoning, and finally the approach is illustrated on a VTOL use case.

5. COMPUTATION TOOL & BACKGROUNDS

5.1 ONERA Model Presentation

The ONERA model simulates the main lightning processes occurring during a lightning strike to the aircraft that V. Mazur [3] inferred from the electric field variation recorded during in-flight lightning experiment [2]. He showed that the lightning strike starts by the inception and the development of positive and negative lightning leaders from the aircraft. This phase lasts few milliseconds during which the aircraft has hardly moved. The second phase lasts few hundreds of milliseconds. During, this period, the lightning strokes strike the aircraft and the motion of the aircraft leads to the displacement of the lightning arc roots on the fuselage.

In this paper, we only present the part of the model focused on the initial lightning leader inception from the aircraft and more specifically on the positive one which is the first electric lightning discharge which incepts from the aircraft. In long sparks laboratory [4], it has been shown that a propagative discharge starts as soon as a leader incepts after a corona ignition. The electric corona charge has to be high enough, typically of few micro coulombs [4] in laboratory, to heat the corona root to 1200°K which leads to the transition of the cold streamer filament to a hot leader. In laboratory, the background electric field is usually much higher than 300 kV/m enabling the long spark to break the air gap and leading to an arc phase. On contrary, lightning leader can develop in electric field one order of magnitude lower than the ones used in laboratory. From artificial triggered lightning measurements, ONERA assumes that a lightning leader develops from a ground structure when the three following criteria are fulfilled:

1. The atmospheric electric field (background field) has to be higher than a threshold called stabilization field which depends on the electric length of the object [5].
2. The enhancement of the background electric field on the structure has to lead electric field higher than the air ionization electric field (3 MV/m at sea level).
3. The corona charge produced for the leader inception has to be higher than Qcrit. Measurements have shown values of corona charge from 20 to 40µC. The corona charge is computed by the simplified method presented in Bondiou et al. [6].

From these criteria, ONERA proposes the following model to compute the initial attachment points for the positive leader. The input parameters for the simulation are:

- the aircraft geometry. A surfacic mesh is performed from the geometry. It is composed of nodes p and triangle faces
- The fuselage materials. The dielectric parts are removed of the meshing
- the distribution of the atmospheric electric field direction generated by the thundercloud,
- the critical corona charge Q_{crit} for a lightning positive leader inception.

The computation steps are the followings:

1. Set an atmospheric electric field direction.
2. Compute the electrostatic electric field on and around the aircraft for a background field of 1 V/m.
3. Compute the electric length of the aircraft for this atmospheric electric field direction (see [7]).
4. Compute the stabilization field from the electric length (see [8]).
5. Compute the electric field streamlines from the aircraft for an atmospheric field equal to the stabilization field,
6. Compute for each streamline from the aircraft, the charge Q at each node of the aircraft meshing.

7. Find the nodes p of the surface mesh of the aircraft where Q(p) is higher than Qcrit and the field on the aircraft higher than 3 MV/m. Compute the probability of attachment by assuming that the probability is driven by the corona charge. The density function fp is given by:

$$f_p(p) = \frac{g_p(p)S_p}{\sum_S g_p(q)S_q} \text{ and } g_p(p) = \begin{bmatrix} 0\ si\ Q(p) < Qcrit \\ Q(p) si\ Q(p) \geq Qcrit \end{bmatrix}$$

Where Si is the equivalent surface of node i.

At the end of this elementary computation phase, the direction of the atmospheric electric field is changed following the field direction distribution. By integrating the results of a given direction on all the directions performed, zones on aircraft of initial positive leader inception are shown.

An example of result is given in Figure 6. The figure shows the probability to have an initial attachment of the lightning positive leader on each node of the aircraft for a uniform probability of the atmospheric field direction. The attachment point (red color) are mainly at the extremity of the blades of the main rotor and at the tail fin and skid. The dark blue color associated with a probability lower 10-10 means that no positive lightning leader can initiate.

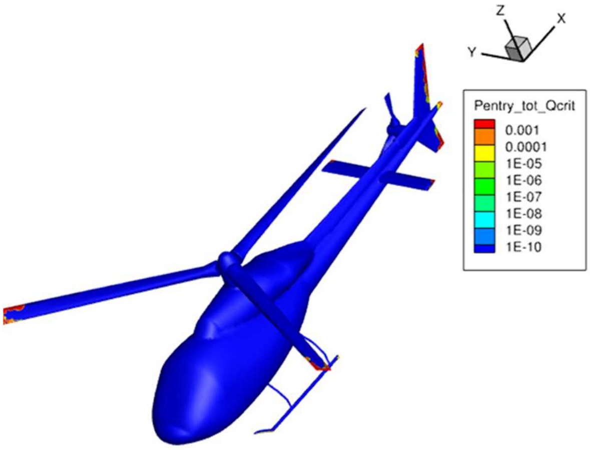


Figure 6: Computation of the probability to have an initial attachment of the lightning positive leader. Qcrit=30µC. A uniform probability of the atmospheric field direction is assumed. Blades rotation 0°.

The Figure 7 shows the cumulated probability on each main part of the rotorcraft as a function of the blade rotation. The effect of the blade rotation is very low on the results. The Table 4 shows values of this probability for two angles of blade rotation.

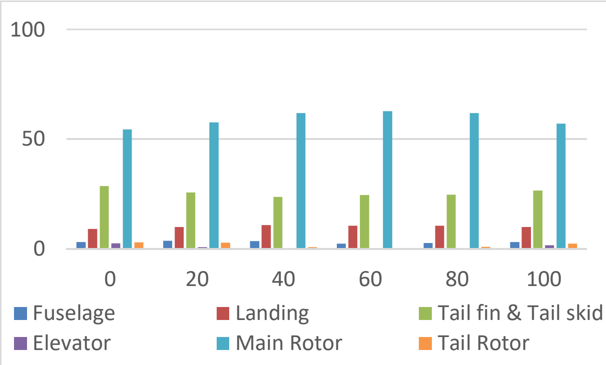


Figure 7: Cumulated probability on main part of the rotorcraft, defined in the legend, for s a function of the blade rotation. The abscise is associated of the angle of rotation in degree of each blade (Main and Tail rotors). A uniform probability of the atmospheric field direction is assumed.

Table 4: Cumulated probability on main part of the rotorcraft, for the two angles of blade rotation (Main and Tail rotors). A uniform field direction in a solid angle of 10° from the vertical is assumed.

Proba Entry (%)	0 deg	60 deg
Fuselage	2,98	2,22
Landing skid	9,1	10,5
Tail fin & Tail skid	28,44	24,43
Horizontal Stab	2,34	0
Main Rotor	54,3	62,74
Tail Rotor	2,84	0,11

As rotorcraft flies at low altitude under the base of thundercloud, the atmospheric field direction is mainly vertical. The computation has been performed assuming a uniform field direction in a solid angle of 10° from the vertical.

Table 5 : Cumulated probability on main part of the rotorcraft, for the two angles of blade rotation (Main and Tail rotors). a uniform field direction in a solid angle of 10° from the vertical is assumed.

Proba Entry (%)	0 deg	60 deg
Fuselage	0	0
Landing skid	0	0
Tail fin & Tail skid	42,75	37,43
Horizontal Stab	0	0
Main Rotor	57,25	62,57
Tail Rotor	0	0

5.2 AIRBUS Model Presentation

Others modellings were also performed with ASERIS (Airbus suite) as, for instance, on A400M (ICOLSE 2005) and H175 (VFS 2020 [10], and in particular ICOLSE 2022 [11]), with comparisons with the experience in-service.

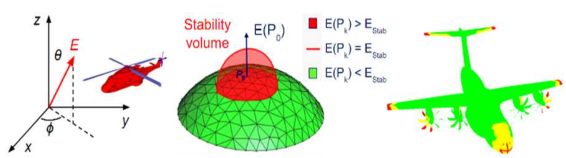
A lightning attachment is likely to occur at a location on the aircraft when conditions for having a leader propagation are fulfilled, corresponding by hypothesis to reaching the streamer-leader transition.

Using an electrical approach, this transition is supposed to be achieved at a point P on the aircraft surface while verifying the two criterions:

1. On the electric field ($E_P > E_{threshold}$ ≡ breakdown field in air, so 30 KV/cm at sea level)
2. On the electrical charge Q_{Stab} available inside a small volume around P (called stability or corona volume) to feed this transition process ($Q > Q_{crit}$ ~ few µC, up to 5 µC)

The modeling principle to determine attachment areas is based on the following sequence:

1. Likely conditions to a lightning strike triggered by an aircraft is modeled by an ambient field in every direction $E_A(\theta,\phi)$, with a typical angular sweeping step of 10°, so it is considered an equiprobability of the ambient field directions
2. Poisson equation is solved to determine the surface charge density on the object (σ_P ≡ normal electric field at any point P)
3. Locations where the streamer-leader transition is likely to be reached in first are obtained by verifying the previous criterions:
   - We determine the location $P_0(\theta,\phi)$ where the E field exceeds in first the breakdown threshold E_{Th}
   - We compute the charge Q_{Stab} contained within the area around $P_0(\theta,\phi)$ and delimited by the iso field boundary $E = E_{Stab}$ (stability field ~ 5kV/cm)
4. Attachment probabilities density are finally derived from a weighted counting of the number of occurrences at each location P and its associated stability area



(a) (b) (c)

Figure 8: Primary attachment locations evaluation methodology. (a): static field simulating the static stress prior to attachment ; (b): stability volume around first air breakdown location ; (c): Primary attachment probability density classified in different probabilities areas (High, Low, Null) [11]

An ICOLSE 2022 paper [11] shown that the modelling results of initial attachment points on a H175 and the experience in service on similar rotorcraft is consistent. Rotors and large protrusions in rear parts identified as the most exposed items while radome and most of airframe present the lowest risks. Nevertheless, calculations let suppose that the horizontal stabilizer would be more struck that it is actually in service.

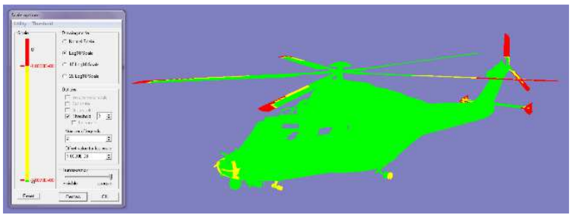


Figure 9: Attachment probability density for the reference H175 case configuration (REF). Likely to be a primary attachment area with high probability; Likely to be a primary attachment area with low probability; Unlikely to be a primary attachment area

The understanding of the source of discrepancy would require more investigation, e.g. considering that for H/C in operation the ambient electrical field is not equiprobable in all the directions because most of the flights are between clouds and the ground/sea what excludes horizontal electrical fields. Another explanation could be that statistics on H/C fleet comprised various designs with different horizontal stabilizers locations leading to different propensity to lightning strike attachment.

The analysis of calculations results shall also considered the model uncertainties and therefore some protrusions, which are not forthwith evidenced as attachment areas by the simulation tool: when the electric field ratio generated at the level of protrusions in “competition” is not significant enough, these other protrusions shall be also considered as potential attachment areas.

Beyond the lightning zoning, an advantage of the calculation is to provide the couple of entry and exit points at stake for any electrical field orientation and the distribution of Electrical field directions involving the different protrusions. For unconventional platform, the analysis of these data can provide more insight for the identification of the lightning scenarios that should be the more likely in operation. That shall not drive the level of lightning protection but this analysis should support the identification of the relevant set of lightning scenarios for which the demonstration effort will be more focused. An example is the definition of lightning scenarios covered during the lightning indirect effect transfer functions test campaign, which is required for showing the compliance of the electrical systems involved in functions with failure conditions classified as potentially catastrophic. A lightning compliance demonstration strategy defined with considering the most likely strike scenarios in a relevant manner is also key for the safety.

6. FIRST INITIATIVES FOR DEVELOPING VTOL ZONING

6.1 EUROCAE WG112 Methodology

The purpose of the document developed by WG112 S/G 9 is to propose a methodology for the elaboration of the lightning zoning of VTOL using a similarity approach.

This method is called Mix & Match (M&M) and consists in considering area per area similarities with Aircraft Rotorcraft zonings for the different flight conditions, e.g. hover and cruising and also the potential propeller mode of operation and finally taking the most severe one.

This method is still in elaboration and may be the method recognized by the industry when the document will be released. A main advantage is this method is to face a great variability in terms of shapes and propeller architecture which can be encountered in the world of VTOL.

6.2 PHYLIGHT 2 Project

PHYLIGHT 2 is a project leaded by ONERA whose has developed with multi-domain optimization (MDO) approach a concept of VTOL called HERMIONE (Figure 10). It is a VTOL for 4 passengers and a pilot for urban mobility. It is composed of 12 electric motors. 4 of them can be tilted during vertical takeoff and landing. The optimization has also been done on safety parameters in order that it can be resilient to engine failures.

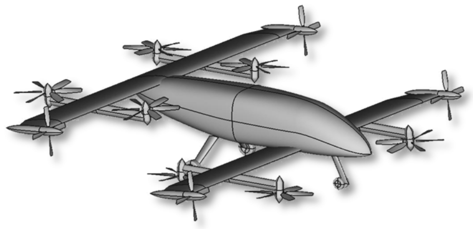


Figure 10 : ONERA VTLO concept HERMIONE

The ONERA model has been applied to this concept to compute the initial positive lightning leader attachment point. A uniform probability of the atmospheric field direction is assumed.

The attachment points of positive leaders are shown on Figure 1. As these zones are small and not well resolved in this figure, arrows show the location of main positive lightning leader attachment points. We can note that for this geometry internal rotors are not exposed to positive lightning leaders. They are protected by the landing gear.

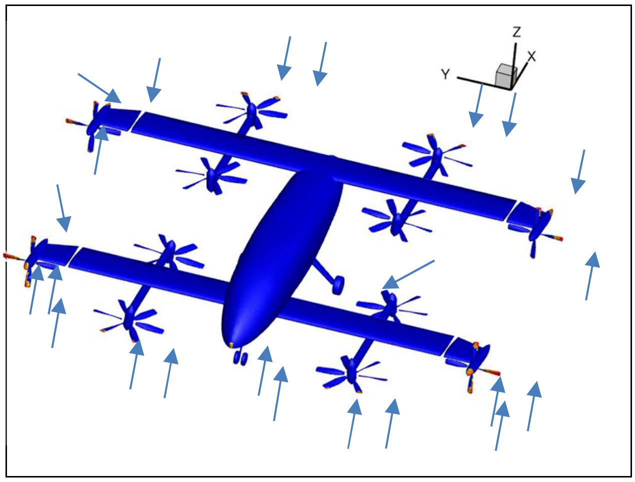


Figure 11: Computation of the probability to have an initial attachment of the lightning positive leader on ONERA VTOL concept HERMIONE. Qcrit=30µC. A uniform probability of the atmospheric field direction is assumed. Cruise flight. The arrows show the attachment points.

7. CONCLUSIONS & PERPECTIVES

The certification to Lightning will be crucial for ensuring the safety of VTOL especially for urban mobility operations in any weather conditions. Then the capability to define a lightning zoning is a pillar for performing the Lightning safety analysis and protecting the VTOL against the Lightning Direct and Indirect effects.

The WG112 S/G 9 is mandated to propose a methodology for the elaboration of lightning zoning, which shall cope with the diversity of emerging designs observed for addressing the future urban mobility. This method, called Mix and Match, is a similarity approach with the existing zonings defined in ED-91A and therefore this method should provide a reasonable worst case where simulation can fail especially if not used properly.

Nevertheless, the calculation can provide valuable additional information for the identification of relevant lightning strike scenarios to be considered in the demonstration process. These scenarios are well known by the industry for conventional Rotorcraft and Aircraft from the experience in flight, but this knowledge needs to be developed for new designs where the simple engineering judgement can be not enough reliable.

For this purpose, this paper shows that the Lightning zoning calculations on helicopters provide some results consistent with the generic zoning of ED-91A recently aligned with decades of experience in service. The lightning scenarios highlighted by the calculation are also consistent with the experience. Then, this work is validating the capability of these calculations to support the certification process, as long as the simulation is employed as an augmented approach in complement of the Mix and Match approach, and not as a unique element.

For VTOL, a first modeling on a use case performed in the frame of PHYLIGHT-2 shows results coherent with the present knowledge of zonings on conventional platforms and therefore produces a zoning consistent with what is issued from the M&M method.

Beyond zoning consideration, the lightning protection effort for VTOL shall take into account the safety implications, in the continuation of already common practices for certifying conventional platforms. Moreover, this analysis shall be conducted as early as possible in the development cycle to avoid late system redesign (e.g. electrical engine and propellers) or architecture modification.

If the published EASA VTOL special conditions and the lightning Acceptable Means of Compliance allow certifying with lightning avoidance means as an alternative to VTOL lightning protection, the FAA is not offering this opportunity today. This may consist in relying on reliable systems for the detection of lightning strike risk or on weather forecasting. This alternative is

reasonable for short duration flight intrinsically limited by the energy storable in batteries.
Nevertheless, the non-protection against the lightning may lead to inacceptable operational impact in some regions of the world where lightning condition is frequent.

As raised during ICOLSE 2022 [11], one question is still open: when different protrusions are in competition for triggering a lightning strike, what would be the criteria for a protrusion to protect the other ones with enough confidence so that it would be acceptable to exclude a primary attachment to the others? This should consider the experience, possibly calculations, the intrinsic random nature of the lightning and the curvature of the lightning channel, and the lightning interception potentiality. The ponderation of the criticality of the hazards versus the potentiality of the event may be also managed by a "tool" formerly existing in ED-91 (initial version before ED-91A this one dated 2018-2019) which is the zone 3N, requiring protection at 40KA and not at the full-level threat, e.g. 200KA.

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