In-flight lightning damage assessment system ILDAS, Tests on-ground and in-flight

IN-FLIGHT LIGHTNING DAMAGE ASSESSMENT SYSTEM ILDAS, TESTS ON-GROUND AND IN-FLIGHT.

A.P.J. van Deursen (1), A. de Boer (2), M. Bardet (3), F. Flourens (4)

(1) Eindhoven university of technology, POB 513, 5600MB Eindhoven, The Netherlands, Email:a.p.j.v.deursen@tue.nl
(2) Dutch National Aerospace Laboratory, POB 90502, 1006 BM Amsterdam, The Netherlands, Email:Alte.de.Boer@nlr.nl, (3) Idem, Email:Michiel.Bardet@nlr.nl
(4) Airbus France, Toulouse, France, Email: FranckFlourens@airbus.com

ABSTRACT

The In-flight lightning damage assessment system ILDAS resulted from a EU-FP6 cooperation of 12 partners. It has successfully been completed with demonstration of operation in 2009. Airbus decided to develop the system further with EADS and NLR. The paper describes the magnetic field sensor selected for this phase 2, and briefly discusses the test on-ground and tests in flights through thunderstorms carried out up to now.

1. INTRODUCTION

At the previous ESA Workshop on Aerospace EMC [1] a set of sensors for the lightning induced magnetic field around an aircraft was described. The sensors were intended for the In-flight Lightning Damage Assessment System ILDAS, a system to determine the attachment points and severity of a lightning strike on an aircraft during flight [2,3]. The ILDAS was developed in an EU FP6 project that started in 2006 with twelve partners [2]. The EU project aimed to develop the full ILDAS, from 1) the capturing of magnetic and electric field data to 2) local storage on-board, 3) off-line data transmission after flight, 4) data storage and 5) data analysis via the inversion of the magnetic field data into scenarios for the lightning current path through the aircraft. This phase 1 was successfully completed in 2009 with ground tests on an A320 aircraft. Of the 18 lightning attachment scenarios tested 17 were correctly identified [4]. Airbus decided to continue the development with EADS and NLR from proof of concept level into an operational system for measurements in a company test aircraft (ILDAS-2).

The TUe contribution in ILDAS-1focussed on the selection and development of the magnetic field sensors, and on the first part of the signal conditioning system. Here the aspects of accuracy, environment and EMC were particularly important. Because of the good EMC properties, a differentiating/integrating system [5] was chosen. Two types of differentiating coil sensors were proposed, intended to be mounted on the wings and the tail air-foils. One was a small 4-turn coil of 10^{-2} m^2 flux capturing area, intended to cover the bandwidth from 100 Hz up to 10 MHz. The other was a multi-turn coil with a flux capturing area of 0.6 m^2. It was mounted inside a metal shield in order to limit the bandwidth to 1000 Hz; the shield kept the subsequent passive/active integrator within its linear response even for a stroke of 200 kA [6]. A third type of sensor is the window sensor that employs the lightning current pattern around a window in the fuselage (Fig. 1). Actually, the window behaves as a fat slot-antenna for the magnetic field outside the aircraft associated with the lightning current through the fuselage. As implemented with the chosen integrator, it is only used for frequencies above 100 Hz.

In the original ILDAS-1 concept twelve sensors were used distributed over the aircraft. The localization of the attachment points relied on the simultaneous measurement of all 12 sensors. One step also taken in ILDAS-2 is the re-evaluation of the system to make it more acceptable for aircraft maintenance, such as: optimize/reduce the number of sensor, limit the components to those in-cabin, etc. Because of advantages in mounting and relaxed requirements on the environment, Airbus selected the window sensor as only type of sensor to be used and these sensors should be employed on the fuselage solely. The inversion of magnetic field data into attachment points has to be carefully reconsidered.

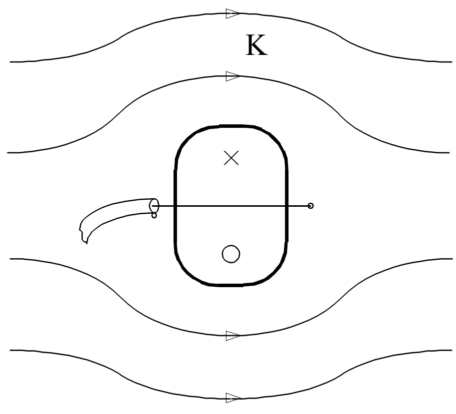

Figure 1. Principle of window sensor, with lightning current density K through aircraft hull. The magnetic field penetration of the window is indicated by × and ○.

The paper presents an analysis of the window sensor. In order to obtain the effective flux capturing area, the details of the window mounting have to be included in the calculation. The data are compared with the A320 ground tests carried out in July 2009. Finally, data from actual flights through thunderstorms, showing that the ILDAS sensors and data acquisition modules worked as intended.

2. ANALYSIS OF WINDOW SENSOR

Figure 1 shows the operating principle of the window sensor. When the window opening is not present, a lightning current density $\mathbf{K}_0$ through the fuselage causes a magnetic field $\mathbf{H_0}$ outside the fuselage oriented perpendicular to $\mathbf{K}_0$**;** K_0 and H_0 are assumed to be homogeneous over the area considered. Both are measured in units of A/m and equal in magnitude. The window opening distorts the current pattern into the shape shown as **K** in Fig. 1. Magnetic flux now enters (×) and leaves (○) the aircraft through the upper and lower half of the window. The flux variations are captured by the inner lead of a coaxial cable, crossing the window at mid-height and connected to the fuselage at the right. The outer conductor is grounded to the fuselage at the left. Analytical expressions exist for the flux Φ through each window half, for the case of a circular window of radius r_0 mounted in a flat and thin fuselage:

$$\Phi = \mu_0 H_0 r_0^{\,2}, \qquad (1)$$

with μ_0 the magnetic permeability of free space. This equation relates the sensor flux to the field in case the window is absent. From (1) one obtains that the effective flux capturing area of a circular window sensor is equal to r_0^2. As a first order approximation, (1) can be used for the actual window assuming a value for r_0 equal to the window axis perpendicular to the current flow. A large contribution to (1) comes from the region near the edge of the window [7] where the analytical expressions for the field diverge. This necessitates a careful analysis [8] that includes the near to elliptical window shape, the thickness of wall, and possible retaining flanges nearby. Here we summarize the results.

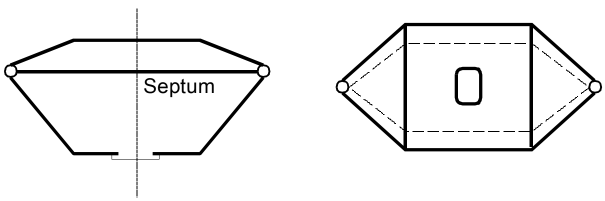

Figure 2. TEM cell with window sensor in the bottom. Left: mid-way cross section. Right: Bottom view from the outside.

In FEKO [9] we assume a TEM cell, where the inside models the outside of the fuselage. The magnetic field is generated by the current through the septum (Fig. 2), driven by two voltage sources indicated by the circles at the ends of the cell. The current returns through the TEM cell walls. The window and the flanges are mounted in the bottom outwards. Fig. 3 shows the cross section view that details the window mounting starting from the window centre. The path of the inner lead of the coax s is indicated by the dashes which is a close approximation of the real path. In order to obtain sufficient accuracy, the TEM cell size was chosen at least four times larger than the window (0.33m×0.23m), and the discretization of the flanges went down to 1 mm size near the edges. Figure 4 shows the window in the TEM cell bottom, together with the meshing, the current density in the metal and the electric field intensity over the area traversed by the sensor wire. The colour coding indicates the current of field intensity. The sensitivity of the sensor was obtained by integrating the induced electric field over the sensor wire path (dashes in Fig. 3).

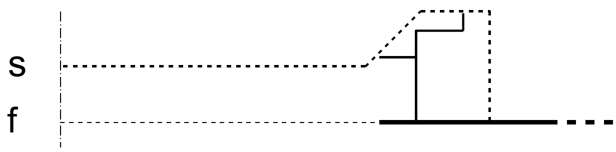

Figure 3.Half cross section of the window at the position of the sensor wire. The fuselage is indicated by f and the heavy line at the right; the sensor wire by s and the upper dashed line. The metal flanges for the window mounting are also shown on top of the fuselage.

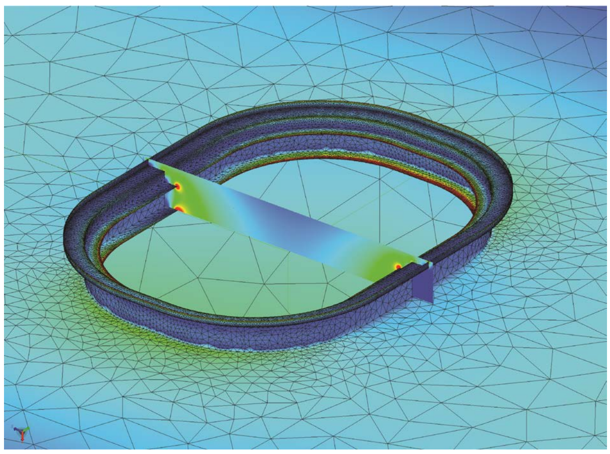

Figure 4. Detail view of the bottom of the TEM cell with window flanges and the applied meshing Current density and electric field intensity are indicated by thermal colour coding.

The numerical approach was calibrated by the model of a circular window of 0.165 m radius in a flat bottom. We obtained an effective area of 271.9 cm^2, within less than 1% of the value of r_0^2. For the actual window shape we found 240.2 cm^2 in a flat bottom without flanges, and 184.2 cm^2 with the flanges present (Fig. 3 and 4). The reduction of the effective flux capturing area by the rounding of the window flanges is about 23%.

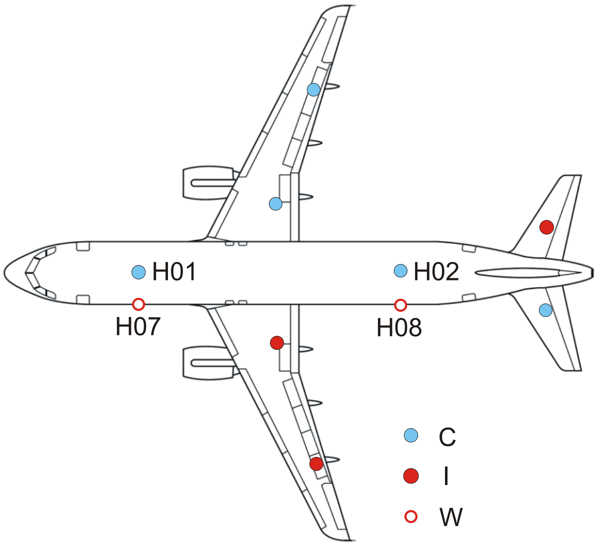

Figure 5. Overview of the 12 position of the sensors on an A320 aircraft. H01 is on top, H02 at the bottom of the aircraft; C stands for Cobham who provided the sensors [10]. Window sensors (W) are H07 and H08. Other sensors (I) are indicated but not discussed here.

3. GROUND TESTS ON AN A320

In June 2009 the ILDAS team carried out ground tests on an A320 instrumented with the full number of sensors (Fig. 5). Details of these measurements are given in [4]. Here the data for the window sensors H07 and H08 are discussed, for the current path from the aircraft nose to tail. The aircraft was placed on top of metal matting acting as ground plane and current return in the shape of a cross under fuselage and wings. The presence of the ground plane influences the current density **K** in the aircraft and causes it to increase at the belly compared to the aircraft in free space. The corresponding magnetic field change over the fuselage can approximatively be calculated by conformal mapping (CM) [8]. The maximum and minimum field occurs at the bottom and top surface of the aircraft fuselage respectively. Local sensors are H01 and H02. The injected current was an aperiodic damped sinusoid with a maximum of 3.1 kA and a time to maximum of about 25 µs. In a fit where only the amplitude could be adapted, the signal from the H08 sensor followed the wave shape of the injected current to within 1%. In Tab. 1 the maxima obtained in measurement run 10 and 11 are given for the four sensors mentioned. The last row shows the CM calculated magnetic fields. One observes a good agreement between measured and calculated magnetic field maxima. The calculated ratio H02/H01 is 4.2; the measured value is 4.1. For H08 the difference between measured and calculated is 5%. For H07 the discrepancy is larger, about 12%. This may be attributed to the proximity of the current injection point and the wing leading edge. From the onset, ILDAS requested 10% accurate field information. Still, the inversion procedure from fields to lightning current path was not hindered by the 12% deviation for H07, as 17 out of 18 scenarios were correctly indentified during the tests [4].

Table 1: Magnetic field in [A/m] at the four sensors, for an injection current of 3.1 kA.

	H01	H02	H07	H08
Run 10	114	466	148	158
Run 11	114	464	147	158
CM	119	503	167	167

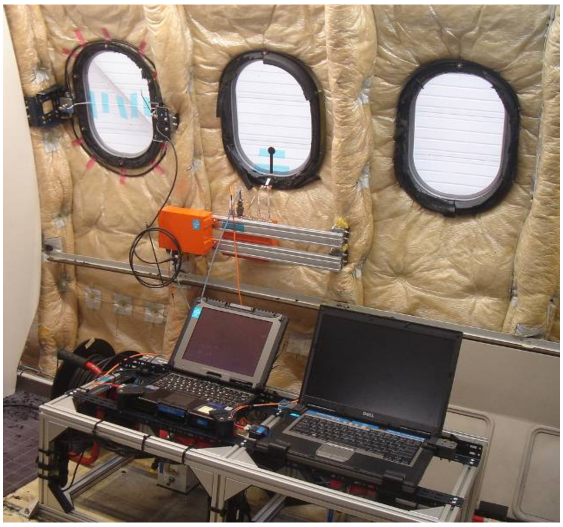

Figure 6. Installation of the test setup in the Airbus A340 aircraft. The leftmost window has the window sensor, the middle window the electric field sensor. The orange box is one of the sensor assemblies performing signal conversion and short term data storage. The laptops record all data during flight.

4. TEST FLIGHTS ON-BOARD OF AN A340

The successes of the on-ground tests in the reconstruction and in the accuracy led to the next step: to test the system in-flight, where conditions are more severe and where electromagnetic constraints are imposed by the lightning strike itself. In these tests, the triggering of the system was also considered, since a final ILDAS should be self-contained. Only two types of sensors were implemented, the window sensor for the magnetic field and a pair of electric field sensors to investigate their effectiveness and the adapted policy for triggering ILDAS. The integrator for the window magnetic field sensor had a bandwidth of 100 Hz – 10 MHz. The electric field sensors had a bandwidth of 100 Hz – 500 kHz (E1) and of 100 kHz to 1 MHz (E2). The data acquisition speed was reduced from designed 100 MHz to 0.4 MHz, to allow a single continuous record during the whole flight with the available data storage. Airbus installed the system in their test-aircraft (see Fig. 6), with electric and magnetic field sensors placed in two neighbouring windows about halfway between nose and leading wing edge.

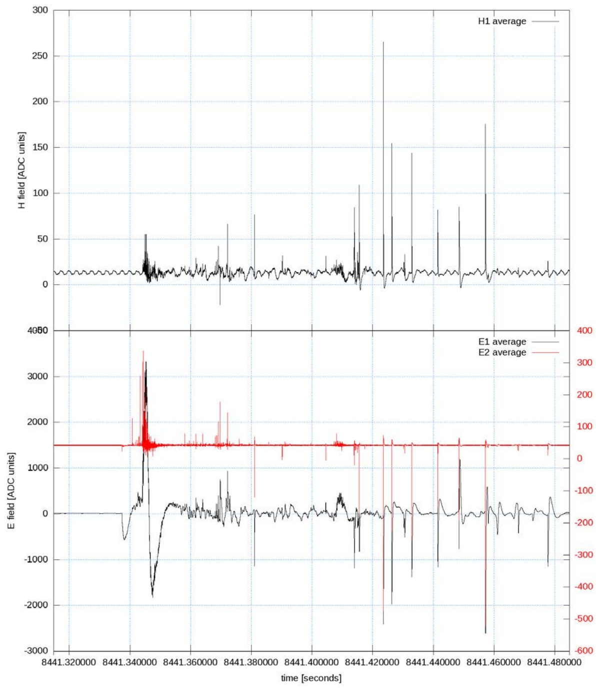

Figure 7. A 200 ms slice of the recording of March 29. Top: H-field window sensor. Bottom:E1 and E2 electric field sensors. Both vertical scales are in uncalibrated ADC units.

Lightning data have been obtained in all three flights in March 2011. A 200 ms portion of 29 March data containing a multi-stroke event is shown in Fig. 7, presented earlier in [11]. Both electric and magnetic field data clearly show about 10 strokes. The series is initiated by unresolved high-frequency phenomena, most likely caused by stepped leader pulse current during initiation phase. The small oscillations in the magnetic field, most clearly visible at the start of the data, are real and caused by magnetic field due to electronic and electrical equipment and its wiring inside the aircraft. The window sensor does not discriminate between inside and outside.

5. CONCLUSIONS OF THE TESTS

The window sensor can be accurately calculated when the details of the mounting flanges are included in the model. An ultimate accuracy is of the order of 3%, well within the ILDAS requirements of 10%.

Ground tests showed that reliable magnetic field data can be obtained with the ILDAS system. On the basis of these data, the inversion process developed in ILDAS-1 correctly identified 17 out of 18 lightning current paths.

The in-flight tests showed that the reduced ILDAS system faithfully records the electric and magnetic field during actual lightning strikes. The electric field data are of interest on their own, but these signals are primarily intended as trigger for a lightning strike with the ILDAS system fully deployed.

6. REFERENCES

1. A.P.J. van Deursen and V. Stelmashuk, Sensors for in-flight lightning detection on passengers aircrafts, ESA Workshop on Aerospace EMC Florence, Italy, 30 March - 1 April 2009
2. EU FP6-030806; see also [on-line]: http://ildas.nlr.nl.
3. S. Alestra et al., "Developing an in-flight lightning strike damage assessment system," ICOLSE 2007, Paris.
4. R. Zwemmer e.a., "In-flight Lightning Damage Assessment System (ILDAS). Results of the Concept Prototype tests", ICOLSE 2009, Pittsfield, Massachusetts, USA.
5. A.P.J. van Deursen, H.W.M. Smulders and R.A.A. de Graaff, Differentiating/integrating measurement setup applied to railway environment, *IEEE Trans. on Instrum. and Meas.*, 55 (2006) pp. 316-326.
6. A.P.J. van Deursen and V. Selmashuk, ILDAS-WP3-021-SA-Integrator test report-v1.7, Internal report ILDAS project.
7. V. Stelmashuk and A.P.J. van Deursen, Analysis of an Inductive Sensor for Lightning Current Measurement, Fitted in Aircraft Windows, Part I, *IEEE J. Sensors* 11 (2011) pp. 199 – 203.
8. A.P.J. van Deursen, Analysis of an Inductive Sensor for Lightning Current Measurement, Fitted in Aircraft Windows, Part II, *IEEE J. Sensors* 11 (2011) pp. 205 – 208.
9. [On-line] http://www.feko.info/
10. J. Hardwick, Cobham Technical Services, U.K.
11. A. de Boer et al., "In-flight Lightning Damage Assessment System (ILDAS): Initial in-flight lightning tests and improvement of the numerical methods," ICOLSE 2011, Oxford, UK.