Sensors for in-flight lightning detection on aircraft

Citation for published version (APA):

Stelmashuk, V., Deursen, van, A. P. J., & Webster, M. (2008). Sensors for in-flight lightning detection on aircraft. In *Electromagnetic Compatibility - EMC Europe, 2008 International Symposium, 8-12 Sept. 2008, Hamburg, Duitsland* Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/EMCEUROPE.2008.4786907>

DOI:

[10.1109/EMCEUROPE.2008.4786907](https://doi.org/10.1109/EMCEUROPE.2008.4786907)

Document status and date:

Published: 01/01/2008

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Sensors for in-flight lightning detection on aircraft

Vitaliy Stelmashuk⁽¹⁾, A. P. J. van Deursen⁽¹⁾ and Matt Webster⁽²⁾

⁽¹⁾ Eindhoven University of Technology, Faculty of Electrotechnical Engineering, Group EPS,
POB 513, 5600 MB Eindhoven, Netherlands, Email: V.Stelmashuk@tue.nl and A.P.J.v.Deursen@tue.nl

⁽²⁾ MW Design (UK) Ltd for Culham Lightning
Abingdon, United Kingdom, Email: matt.webster@culham.com

Abstract— Commercial passenger aircraft are on average struck by lightning once a year. The In-flight Lightning Strike Damage Assessment System (ILDAS) project is to develop and validate a prototype of a system capable of in-flight measurement of the current waveform and reconstruction of the path of lightning current. This paper discusses the various magnetic sensors, their rationale and some tests. Inductive sensors require an integrator in the signal conditioning. Much attention has been paid to the passive integrator, which is the first integrator stage preliminarily responsible for EMC.

Keywords- aircraft; lightning strike; magnetic sensor, passive integrator

I. INTRODUCTION

In-flight statistics show that a commercial airliner can expect one lightning strike per year. The lightning current measurements is essential for two reasons. Firstly, to build up a better knowledge of the parameters of a lightning strike to fixed-wing aircraft which can be used to improve aircraft design and secondly, for the development of tailored and efficient maintenance inspection procedures, which must be applied after a recorded strike. Our responsibility in the ILDAS project is to design and develop the sensors which are able to capture and measure lightning current during flight.

The knowledge about lightning strike is based on three major research programs studying lightning strike interaction with aircraft: NASA Storm Hazards program, USA/FAA Lightning Characterization program, ONERA/CEV Transall programme. The in-flight measurements have shown that typical waveforms of lightning current consists of five components (see Fig.1) [1] covering 98% of the lightning strike. The parameters of current waveform are presented in Table I. The most important for direct effects damage are the continuing current (high charge transfer) and the return strokes.

We measure the magnetic field generated by the current through the aircraft as a probe for the current distribution. A two-sensor approach is preferred, one for the fast components A, D and H in Fig. 1, and another

Figure 1. Typical waveform of the discharge current during a lightning strike. sensor optimized for the low-amplitude slow component C.

for high frequency components. A good solution is an induction coil sensor based on Faraday's law followed by an integrator. An example of such induction coil as a sensor for ILDAS has earlier been described in [2]. We will discuss the window sensor as special type proposed for ILDAS. The design of the passive integrator will be presented. The passive integrator is the first stage in the signal conditioning, and is followed by an active integrator. Two approaches are available for the C-sensor, again an inductive coil and a solid state sensor. Here we only discuss the solid state sensor. It should cope with the large magnetic field of the short time strokes. The A and D strokes may cause sensor's saturation and thereby distortion of the measured signal. An appropriate shield can sufficiently reduce A and D magnetic field. The shield design and solid state sensors selection will be presented.

TABLE I. LIGHTNING CURRENT CHARACTERISTIC

Lightning phase	Lightning characteristic			
	Minimum amplitude	Maximum amplitude	Minimum frequency	Maximum frequency
Continuing current (C)	± 40 A	± 900 A	1 Hz	100 Hz
Strokes (A, D)	± 1 kA	± 200 kA	10 kHz	20 MHz
Bursts (H)	± 100 A	± 10 kA	200 kHz	≥20 MHz

II. DISCUSSION

A. Shield design

Consider a metal sphere, $2r_0 = 10$ cm diameter, $d = 2$ mm wall thickness. Kaden [3], approximates the magnetic shielding Q_h of such a sphere by analytical expression:

$$Q_h^{-1} = \cosh(kd) + (K+2/K)\sinh(kd) \quad (1)$$

with $k = (1+j)/\delta$, δ is the skin depth at frequency f . A plot of $|Q_h|$ for a copper shield is given hereunder (blue line). The shield starts to attenuate fields at 60 Hz, above 6 kHz (see Fig. 2) the skin effect ensures additional exponential attenuation.

Figure 2. Calculated reduction for a spherical shield as function of frequency.

For the relevant frequencies below 100 kHz, the amplitude of Q_h can be approximated by four poles (green line). This approximation also fits the phase sufficiently well. The calculated signal of the A component inside, assuming 10^4 A/m amplitude outside such a shield is given in Fig. 3. It can be seen that the A component is slowed and reduced. We infer from the data that the slow signal channel should attain a maximum output at a magnetic field of the order of 1 kA/m.

B. Solid State Sensors

The preliminary selection of the sensors has been already discussed in [2]. We evaluated the magnitude of continuing magnetic field (C component) in some sensor's locations using data from Table 1. It was found that the sensor placed on fuselage is exposed to the lowest magnetic field, which is of the order of ± 15 A/m. The maximum magnetic field is about ± 100 A/m; it

Figure 3. Calculated signal from a sensor inside the shield subjected to four A-waveform surges. (peak value outside is 10^4 kA/m, inside 310 A/m)

occurs on the wingtips. But from Fig. 3 the maximum field due to the A component is 300 A/m. Therefore the low frequency sensor should measure magnetic field from ± 15 A/m to ± 1 kA/m which is the dynamic range of 36 dB. At that moment we have two candidates for prototype testing: GMR (giant magneto resistance) sensor AAL002-02E [4] and AMR (anisotropic magneto resistance) sensor HMC1022 [5].

The AAL002-02E is a one-axis GMR sensor manufactured by NVE Corporation with low hysteresis GMR material. It is temperature tolerant, from -50° to $+150^\circ$ C. The NVE GMR sensors have unipolar magnetic characteristic which means that output of the sensors is the same for the magnetic fields with different field directions. A bias magnetic field can be used to make sensor bipolar. For this aim, a small magnet was put near the sensor creating a magnetic field of about 1 kA/m with output zero point at 15 mV. The signal from the sensor was preamplified by the instrumentation amplifier INA117 and filtered by a low frequency filter with AD820 with a cutoff frequency of 150 Hz and amplification factor 25. The last stage is the buffer amplifier with an output impedance of 50 Ω . The overall gain is 50; the voltage source for the sensor bridge is ± 15 V. The sensitivity measured in a test is $9 \mu\text{V/V}/[\text{A/m}]$. At 30 V bridge voltage and 30 times amplification, the measured noise level is 3 mV peak to peak at the bandwidth up to 100 Hz. The noise corresponds to 0.4 A/m. The temperature dependence of the AAL002-02E was also measured (see Fig. 4) and it agrees quite well with the data ($0.1\% / ^\circ\text{C}$) presented in NVE catalogue [4]. The signal changes by 15% over the temperature range from -55° to $+85^\circ$ which covers to the ILDA temperature requirements. The dynamic range is large

Figure 4. Temperature dependence of AAL002-02E

enough to measure continuing current and in presence of the strokes.

Honeywell's magnetic sensor HMC1022 is two-axis AMR bridge device equipped with set/reset and offset stripes. It can work at wide magnetic field range ($-80 \div +80$ A/m) and is sufficient for ILDAS temperature range from -55° to $+125^\circ$. The amplification circuit is identical to the circuit with AAL002-02E with different amplification coefficient 140. The measured sensitivity of HMC1022 is $1 \mu\text{V/V}/[\text{A/m}]$ ($10 \mu\text{V/V}/[\text{A/m}]$ in [5]). The noise level is 10 mV peak to peak (magnetic field 0.5 A/m) at bandwidth up to 100 Hz. The measured output change with temperature is 35% in the temperature range from -55° to $+85^\circ$ (Fig.3) which is the same value as bridge resistance change (bridge resistance change is $0.25\%/^\circ\text{C}$) presented by Honeywell [5].

Figure 5. Temperature dependence of HMC1022

C. Window sensor

ILDAS system has 12 sensor assemblies ultimately. Every sensor has to be placed on the surface of an

aircraft. One of the serious problems of the project from the point of view of requirements, technology and safety is to mount sensors outside the cabin. A sensor that could completely be mounted inside the aircraft would be a good solution; for drawing see Fig. 6. The sensor's geometry is designed in such way that it captures the magnetic field penetrating through the window. The sensor output is proportional to the magnetic field H_0 that would have existed at the outside of the fuselage without the window.

Figure 6. Window sensor

Kaden in [3] gives the mathematical expression for the magnetic field penetrating a circular opening in an infinite conductive plane:

$$H = H_0 r \sin \varphi \left[\frac{1}{2} \sin \vartheta + \frac{2}{\pi} \sum_{m=2,4,6..}^{\infty} \frac{(-1)^{\frac{m}{2}}}{m^2 - 1} \left(\frac{r}{r_0} \right)^{m-1} P_m^1(\cos \vartheta) \right] \quad (2)$$

with H_0 the strength of the magnetic field parallel to the plane, r_0 the radius of the hole, r the distance to the centre of the hole, ϑ the angle between axis perpendicular to the plane and r . Using (2) and substituting $\vartheta=90^\circ$ we can calculate flux through the half of the hole (the second half has opposite direction of magnetic field):

$$\Phi = \mu_0 \iint_S \vec{H} d\vec{S} = \mu_0 H_0 r_0^2 \quad (3)$$

The overall flux captured by the window sensor is 2Φ .

A test of a window sensor was made by Culham during a simulated lightning test by BAE Systems to a Nimrod aircraft installed in a return conductor rig surrounding the aircraft from the nose to the tail extending over the wings. The current was injected on the nose refuelling probe and extracted on the underside of the rear fuselage. The probe was constructed from a figure of

eight loop of black RG223 50 Ω coaxial cable mounted on the window (see Fig. 7).

Figure 7. Picture of the window sensor mounted on the window of Nimrod aircraft (photo courtesy BAE Systems).

A passive integrator with a 477 μ s time constant was connected to this loop.

The aircraft was injected with pulses with a waveform approximately the same as component A (Fig.1) and amplitude of 34kA. The input current to the aircraft and the output from the sensor are shown on Fig. 8. It can be seen the window sensor output reproduces the injected current with good suppression of noise. The slight additional droop is caused by the lack of the active integrator. No correction to the data was applied at low frequencies. The practical installation in the test was such the sensor was not ideally positioned in the window: the outer rim should have been against the inside wall of the airplane at some distance from the window, rather than covering the window area. The inner panelling on the airframe prevented us placing the sensor close to the aircraft skin

Figure 8. Injected current and output signal from integrator on window sensor.

D. Integrator

The passive integrator is the first step in the signal processing. This component has a number of functions:

- 1) terminate the signal cable into its characteristic impedance,
- 2) filter the signal and limit the dynamics to an acceptable level for the subsequent electronics,
- 3) act as determining element in the composite integrator frequency characteristic,
- 4) filter the signal against any unwanted interference outside the frequency band of interest.

A passive integrator with good high-frequency characteristics has been described by Raleigh [6]. The construction is coaxial with brass outer conductor and BNC connectors on both ends. The integrating capacitor is a longer section of very low impedance line (graphite) insulated with Mylar. We built a prototype based on similar principle. It showed suitable operation, with intended roll-off and, most importantly, also with efficient interference blocking, at least up to 1.8 GHz. However such a construction is less suited for ILDA firstly, because of the size (the low impedance line must have sufficient length) and secondly, because it is difficult to make a good contact between graphite and metal conductor in the high vibration environment.

The integrator with ceramic capacitors was proposed. The sketch is presented in Fig. 9. There are two stages.

Figure 9. Integrator with ceramic capacitors.

The first stage with a roll off frequency 10 kHz is responsible for the integration of the signal up to 20

MHz and must have stable frequency characteristics at broad temperature range from -55° to 85° . The temperature stable capacitors 3.3 nF from AVX were used. The second stage should guarantee unwanted signal attenuation above 20 MHz; the temperature stability is less important in this case. First a feed-through capacitor 62 pF was chosen. Figure 10 shows that the integrator lacks attenuation above 50 MHz, due to the properties of the dielectric in the feed-through capacitor. We are working now on decreasing the size of the integrator by using SMD capacitors instead of ceramic in the first stage and to replace the feed-through capacitor by three microwave SMD capacitors in the second stage.

Figure 10. Frequency characteristic of integrator.

CONCLUSIONS

The continuous current (C component) is of interest, because of its high charge transfer and its contribution to damage of aircraft panels at the attachment point. We have tested two solid state sensors sensitive enough to measure it.

For the fast stroke currents, a special internal window sensor as a replacement of external coil sensors was proposed. Tests on an aircraft subjected to simulated strikes proved that such a sensor is viable. Careful installation procedures need to be given to get a calibrated measurement. The frequency characteristic of a second version of the passive integrator was measured. It showed suitable operation, with intended roll-off and, most importantly with efficient interference blocking up to 100 MHz. The new smaller version with better frequency characteristic is now manufactured.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of this research through the European Commission under contract FP6-030806. We would also like to thank BAE Systems who allowed us access to the Nimrod aircraft during their tests to install and measure the performance of our sensor.

REFERENCES

- [1] A. Larsson, P. Lalande, A. Bondiou-Clergerie, A. Delannoy, "The lightning swept stroke along an aircraft in flight. Part I: thermodynamic and electric properties of lightning arc channels," *J. Phys. D: Appl. Phys.*, vol. 33, 2000, pp.1866–1875.
- [2] V. Stelmashuk, A. P. J. van Deursen, R. Zwemmer, "Sensor development for the ILDAS project," *EMC Europe Workshop*, Paris, June 14-15, 2007.
- [3] H. Kaden, *Wirbelströme und Schirmung in der Nachrichtentechnik*, Berlin: Springer, 1959, 2nd ed, pp.85-89, pp.242-247.
- [4] NVE catalogue, [on-line] www.nve.com.
- [5] HMC1022 datasheet, [on-line] www.ssec.honeywell.com/.
- [6] M. Raleigh, R.E. Pechacek, "Fast Passive Integrator", *Rev. Sci. Instrum.*, vol. 55, 1984, 2023-2026