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The AMPWISE Project

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***Abstract* – This paper presents an energy autonomous Wireless Sensor Network (WSN) for monitoring the structural current in aircraft structures. A hybrid inductive/hall sensing concept is introduced demonstrating 0.5 A resolution, < 2% accuracy and frequency independence, for a 5 A – 100 A Root-Mean-Square (RMS), DC-800 Hz current and frequency range, with 35 mW active power consumption. An inductive energy harvesting power supply with magnetic flux funneling, reactance compensation and supercapacitor storage is demonstrated to provide 0.16 mW of continuous power from the 65 µT RMS field of a 20 A RMS, 360 Hz structural current. A low-power sensor node platform with a custom multi-mode duty cycling network protocol is developed, offering cold starting network association and data acquisition/transmission functionality at 50 µW and 70 µW average power respectively. WSN level operation for 1 minute for every 8 minutes of energy harvesting is demonstrated.**

I. INTRODUCTION

The advancement of aircraft in terms of safety, efficiency, reliability, cost-effective maintenance and passenger comfort is expected to rely largely on sensing technology.

In this paper, an energy autonomous aircraft current monitoring system is introduced, designed for measuring the current flow through the aircraft structural beams, which are used as the return current path of its main electrical power installation. It comprises a differential hall sensor system, an inductive power supply developed for coupling to structural currents, a low power microcontroller and RF communication unit, and a low power protocol developed for enabling sub – mW average power operation while addressing certain aircraft and sensing scenario specifications. The overall system design is confined to industrial aircraft specifications and a certain sensing use case. Its performance is evaluated on a full-size industrial aircraft beam setup, including qualification evaluation for flight testing.

The rest of this paper is organised as follows: The aircraft sensing use case is described in Section II. In Section III, the sensor node architecture including control and communication, sensor and front-end electronics, power supply and packaging are presented. An evaluation summary of the system as a whole is given in Section IV. A conclusion and an outlook for further use and development are presented in Section V.

II. SENSING REQUIREMENTS

In aircraft made of composite, non-conductive materials, the return current of the electrical networks passes through the aluminum alloy structural beams of the airframe. As the role of electricity in aviation is extended to new functionalities, the effect of increased current flow to the electrical infrastructure needs to be evaluated. More specifically, the distribution of the return current path to the structural beam network is of key interest, as beam-to-beam junctions may be affected, resulting in heating, contact degradation (potentially including electromigration effects) and high contact resistance which can increase the risk of hazard. The objective of the sensing use case is to provide a dynamic mapping of current distribution through the aircraft airframe during flight.

A priority for aircraft sensor networks is wireless functionality and energy autonomy, due to the increased significance of weight reduction and infrastructure simplicity in aircraft installations. Therefore, a wireless, energy autonomous and non-invasive monitoring system for aircraft structural currents is targeted.

The current measurement range and resolution is set to 5 A – 100 A and 0.5 A respectively, for direct current (DC) as well as for alternating current (AC), in root-mean-square (RMS) values, with a frequency range between 360 Hz and 800 Hz. The expected minimum average AC current availability is set to 20 A RMS. This value was defined by an internal study in which the aircraft structural current distribution of over 700 electrical loads, supplied using 28V, 115 V or 230 V was analyzed.

Power autonomy adequate for system cold starting and data acquisition once every 8 minutes is required. A total mass for each sensor node in the 50 g range is desirable for practical installation. Synchronization among SN in the 1 ms range is also desirable.

III. SENSOR NODE DESIGN

A. Overview

The sensor node architecture (Fig. 1) is based on the Nordic Semiconductor NRF52840 SoC, which combines an ARM Cortex M4 microcontroller with a 2.4 GHz low power communication transceiver. The structural current is measured by a differential pair of combined hall-effect and inductive sensors, driven and read by an advanced low-power front end circuit. Both systems are powered by an inductive energy harvesting power supply that collects energy from the AC magnetic flux around the current carrying structure. The power supply includes a power management system based on the Texas Instruments BQ25570 microchip, dual voltage regulation and super-capacitor energy buffering. All systems are integrated into a package suitable for installation on the aircraft structural beams described in Section II.

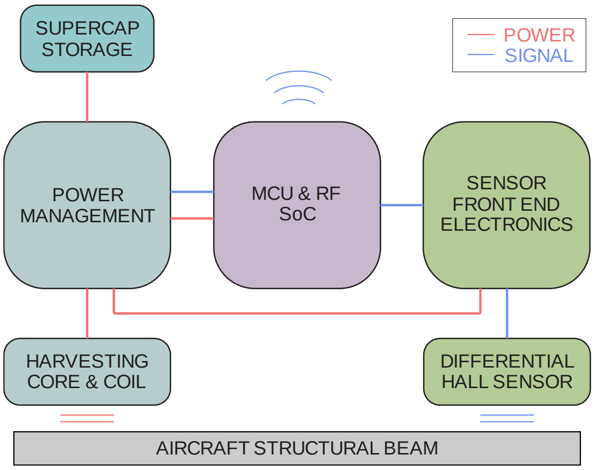

Fig. 1. Block diagram of the Sensor Node.

The overall design is focused on achieving energy autonomy, within the functional specifications required for the use case of Section II. The power consumption measured on each submodule is summarized in Table 1. Each module can be controlled to operate in one of several duty cycle regimes among shut down, sleep and one or more active modes. The sensor node may operate in three different functionality modes: network association, data acquisition/transmission and sleep. Each operating mode uses different duty cycling scenarios, resulting in different average power requirements. The overall average power consumption must be covered by the average harvested incoming power, and higher power modes can be accommodated by the supercapacitor energy buffer for short operating durations. Therefore, power autonomy performance depends not only on energy harvesting provision and electronic component consumption but also on sensor node operation scheduling and on the network protocol.

Table 1. measured consumption of the sensor node.

Module	Mode	Current mA	Power mW
NRF52840 SoC	Active, Acquisition	3.6	6.48
	Active, TDMA TX	25.2	45.4
	Active, TDMA RX	14.5	26.1
	Sleep	0.002	0.0036
Senis AG Structural Current Sensor	Acquisition	7	35 (5V)
	Sleep	< 0.001	< 0.005
Total Sensor Node	Max	32.2	80.4
	Sleep	< 0.003	< 0.0086

B. Communication Module

The communication module is implemented in the 25 mm by 25 mm PCB shown in Fig. 2. The central element is a Nordic Semiconductor nRF52840 communications and micro-controller unit (MCU) system-on-chip (SoC), The nF52840 provides 2.4 GHz low power proprietary communication modes. The MCU is a powerful, yet low power consumption, 64 MHz Arm Cortex M4 with 1 MB program memory and 256 KB RAM.

An external real time clock provides the system alarm clock and metronome. The ability to program a wake-up interrupt enables the nRF52840 to be completely shut down and awaken the next time it is needed. The low deviation of the real time clock, compared to a quartz clock, allows ultra-optimized implementation of the time division multiple access protocol (TDMA), with minimal guard times to compensate deviations, even with large intervals between communication events.

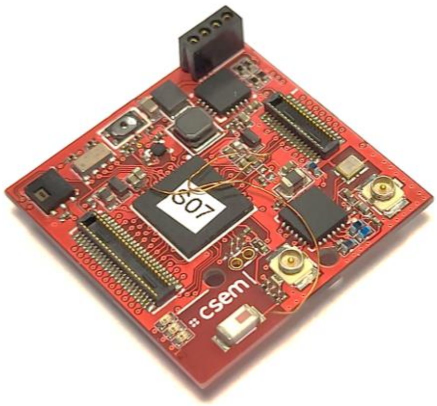

Fig. 2. The communication PCB (25 x25 mm)

C. Structural Current Sensor

The current flow through the structural beam is measured indirectly, through the magnetic field around the beam. Although the current frequency is relatively low (< 1 kHz), the skin effect is significant, due to the large size of the beam cross-section [1]. Indicatively, at 300 Hz the skin effect depth is below 5 mm for an aluminium conductor, which is smaller than the beam cross section dimensions. The AC current is thereby pushed to the beam edges. The current distribution is non-uniform and frequency dependent. The implemented current sensor combines a Hall sensor and a pick-up coil oriented as shown in Fig. 3. The Hall based sensor was selected due to its DC and AC magnetic field measurement accuracy and its small dimensions and weight.

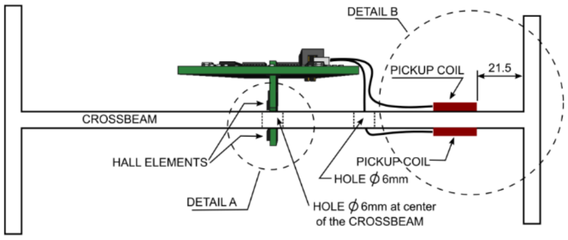

Fig. 3. Current sensor design comprising a couple of Hall sensor and pick-up coil positioned asymmetrically in an antiparallel configuration.

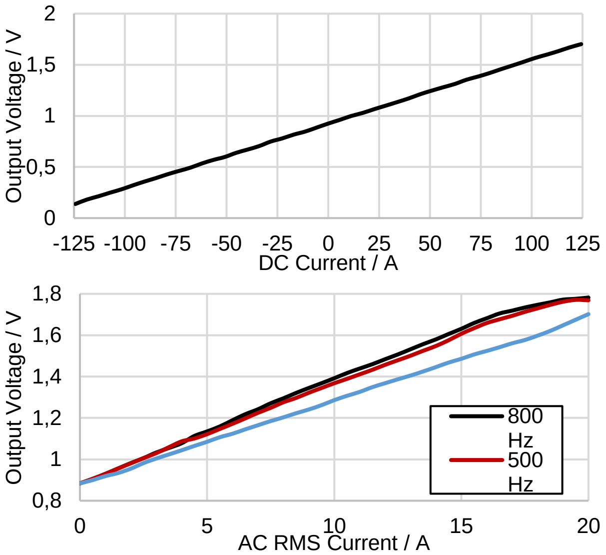

Fig. 4. Up: Voltage output vs DC current. Down: Voltage output vs AC current

Indicative performance results of this sensor system are presented in Fig. 4. A linear relationship between the structural current amplitude and voltage output is observed both for DC and AC measurements, with a distortion for currents over 15 A RMS at 500 Hz and 800 Hz. While the hall/inductive sensor combination demonstrate remarkable frequency invariance between 500 Hz and 800 Hz, the 360 Hz shows a significant deviation. This deviation could be compensated by hardware or data analysis calibration. The output voltage to structural current correlation shown in Fig. 4 demonstrate a worst-case resolution and analysis of 1% and 2% respectively, limited by the signal-to-noise ratio of the voltage output of the hall and inductive transducers.

Table 2. Structural current sensor performance

Feature	Value
Current / magnetic sensitivity	5 mV/A, 2.5 V/mT
Measurement range	5A – 100A
Frequency range	DC – 800 Hz
Resolution	<1% (0.5A)
Accuracy	<2% (1 A) @ 50 A
Current consumption:	7 mA at 5 V DC
Total dimensions and weight	75 mm × 37 mm, 17g

D. Power supply

The power supply module comprises an inductive energy harvester suitable for collecting power from structural currents and a power management system. The energy harvesting concept is illustrated in Fig. 5. A coil with a soft magnetic core is coupled to the magnetic field around the structure, by installation at an edge location where a higher magnetic field is available due to the skin effect, as illustrated in the inset. A funnel core shape is employed to guide flux from a given area through a smaller cross-section, thereby amplifying flux density, and increasing the voltage and power output. A transducer design with optimal coil/core mass ratio is used for maximum transducer power density. These two methods have been introduced in [2] and can provide combined power density increase of as high as two orders of magnitude.

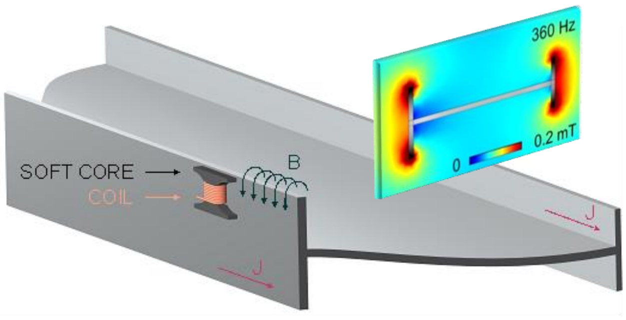

Fig. 5. The concept of inductive energy harvesting from structural current running through an aircraft beam. Inset: indicative simulated magnetic flux density distribution of a 25 A RMS, 360 Hz current illustrating the skin effect.

A photograph of the energy harvester is shown in Fig. 6. It is based on a 10,000 turn, 60 μm Cu wire coil of 6.7 g mass which forms a 20 mm long hollow cylinder with 5 mm and 11 mm inside and outside diameter respectively.

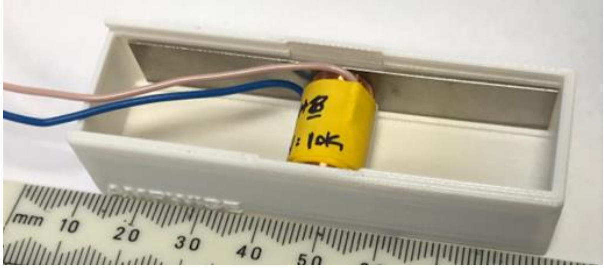

Fig. 6. The inductive energy harvesting transducer (sliding lid not shown).

The power management architecture of the power supply is based on a voltage doubler rectifier in combination with boost and buck converters for supercapacitor energy storage and regulated voltage provision. The rectified output is boosted to a higher voltage level (up to 5.5 V) to allow efficient storage on a supercapacitor. For this purpose, the Texas Instruments BQ25570 is employed [3], which also includes a cold starting booster, maximum power point tracking, secondary storage capability and a buck converter for selectable regulated output.

The power supply has been tested both under emulated magnetic fields and on a full-scale industrial aircraft beam rig, in integration with all sensor node electronics. The harvester output power measured on an ohmic load as a function of structural current amplitude is shown in Fig. 7.

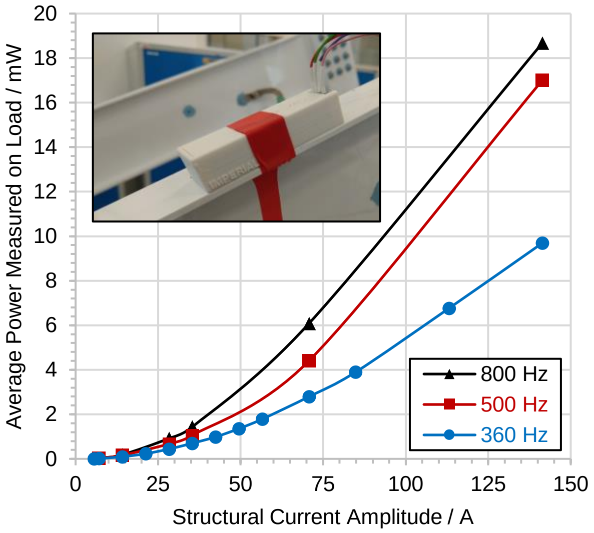

Fig. 7. Harvester output power measured on an ohmic load at half-open-circuit voltage conditions. Inset: The device installed on the industrial test rig.

IV. INTEGRATED SYSTEM TESTS

Flight qualification tests of the complete WSN were performed at an industrial avionics qualifications facility. Wireless communications including multi sensor node pairing and scheduled measurement packet delivery were demonstrated, using two inductive energy harvesting powered sensor nodes. The total power requirements of each sensor node during network association and data acquisition were measured to be 1.1 mW and 0.96 mW respectively. These measurements agree well with the 1.1 mW power consumption observed in the harvesting power supply tests.

Table 3 summarises the overall system performance compared to the specified use case.

Table 3. Demonstrated performance vs use case

Use Case Specification	Demonstrated Performance
Measurement range 5 A -100 A, DC–800 Hz	5 A -100 A, DC–800 Hz
Measurement resolution 0.5 A	< 0.5 A
Measurement accuracy 1%	< 2%
Up to 300 nodes, 30 m range	Supported by RF platform
One measurement / 8 minutes	One measurement / 8 min
Power Autonomy	1 min every 8 mins at 20 A
Measurement synchronization 1 ms	12 μs

V. CONCLUSION

An energy autonomous WSN for monitoring the structural return current path on aircraft during flight was demonstrated. This was enabled by the introduction of a hybrid inductive and hall effect differential sensor for structural currents in combination with hardware filtering for a flat frequency response, and a sensing power consumption of 35 mW. In addition, a low-power sensor node platform with a custom networking protocol that enables duty cycling during both network association and acquisition/transmission. The average power requirement is as low as 70 μW for network association and 50 μW for acquisition/transmission, comparable to the 37 μW of sleep mode consumption.

An inductive energy harvesting approach based on magnetic flux funnelling was adopted and a cold-starting bipolar power management circuit was introduced. The harvesting system was demonstrated to provide energy for a measurement rate of at least one sample every 8 minutes as required by the use case specifications.

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