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Energy Harvesting for Wireless in Flight Testing on A321 Aircraft

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Abstract *In this paper we present experimental results related to the implementation on an Airbus A321 of a power supply for wireless sensors deployed for aerodynamic flight tests. This autonomous battery-free power supply is capturing, managing and storing primary energy from the environment, using solar light and photovoltaic cells. The specifications are detailed, the general architecture is presented and justified together with the identification of devices, and flight test results are given.*

Introduction

Air transport is now an essential pillar of modern society, and a major driver of global economic prosperity. Aviation forecasts show massive traffic increase, both for passengers and cargo, in the next decades. Therefore, air transport is facing various challenges such as fossil fuel consumption, pollutant and noise emission, air traffic congestion, business model, safety and security.

Technological innovations are therefore pursued in the area - among others - of engines, aircraft structural design, and structural new materials. Other innovations are taking place through the concept of More Electric Aircraft (MEA) that is an evolution starting with fly-by-wire (a full electronic interface replaces the classical electro-mechanical interface between pilots and aircraft systems), and evolving through drive-by-wire (no more physical connection – mechanical, pneumatic or hydraulic – between sensor and actuator) to power-by-wire (where pneumatic, mechanical and hydraulic power distributions are replaced by an electric power grid, except for propulsive power) [1]. However, aviation's progress will also be carried out by an increased integration of cyber-physical systems into aircraft [2] for managing baggage, cargo, personal electronic devices, flight deck tasks and helping maintenance through Structural Health Monitoring (SHM) [3].

In that context, Wireless Sensor Networks (WSN) have been considered for various aeronautical applications, such as SHM [4] and flight tests. Each node of this network would perform sensing, data processing and wireless transmission of information. Such wireless networks will hopefully permit (often new) functions without the need of adding extra wiring to an already large burden. However, these nodes need to be self-powered, many of the advantages of wireless sensor networking being obviously lost if external (i.e. wired) power sources were used. For this purpose, batteries offer a high energy density at low cost. However, there are critical drawbacks associated with the use of batteries (such as safety, maintenance cost and environmental issues) prohibiting them in many circumstances in the context of aeronautics.

In this paper we present experimental results related to the implementation of energy harvesters in airliners for the purpose of flight tests. In the following section we describe the requirements of our application, and then we introduce the devised architecture and the selected devices in the next sections. In a last section we discuss experimental results and finally identify directions for future work in the conclusion.

System Global requirements

The total electric cable length installed in an Airbus A380 is 500 km and the extra wiring required for flight tests is 300 km, i.e. 60% of the regular wiring. Generally speaking, this wiring is often difficult to implement and may be realized by bonding the cables using adhesive tapes for the instrumentation outside aircraft structure (Fig. 1), or passing cables through multiple bulkheads by removing screws, bolts or rivets, or even by drilling holes when permitted (rarely allowed in composite materials) that is a cumbersome process, not to mention the multiplication of connectors.

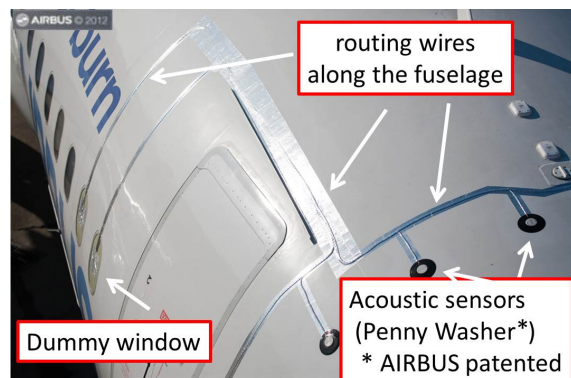


Fig. 1. Example of a classical wired connectivity for outside sensing. The dummy window is used to interconnect the outside sensors with in-cabin equipment

So, even if the application detailed in this paper is of interest to flight test departments of aircraft manufacturers only, it is a critical issue because flight-testing is essential to validate a design and obtain certifications from government agencies, while being expensive, complex and time-consuming.

Among the typical measurements performed during

flight-tests, are pressure sensing at tens of positions around wings, tail, rudder and fuselage (see Fig. 1). In the case of implementations on wings, pressure gloves - themselves accommodating tens of sensors - are affixed to the aircraft outside skin, together with cables connecting them to data loggers. The replacement of this apparatus by Wireless Sensor Networks (WSN) would reduce design load, installation and relocation time (Fig. 2).

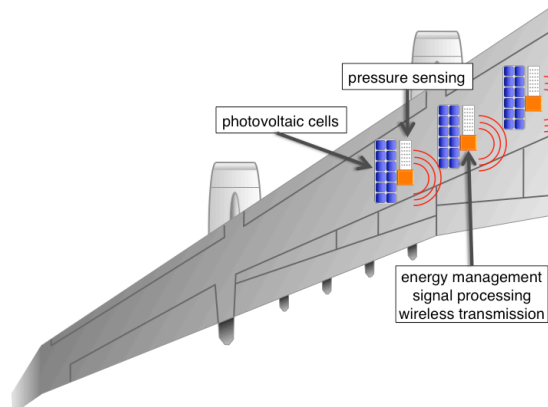


Fig. 2. Objective of our study: deployment of wireless pressure sensor networks, associated with photovoltaic energy harvesting. Three systems are shown.

Considering that a wireless implementation is chosen, the simplest way for gaining autonomy in energy is to use an energy reservoir such as a primary electrochemical battery. But, as already mentioned, their performance is strongly altered by the extreme (low) temperature encountered outside aircraft at cruise altitude, not to mention safety issues raised by some technologies.

Energy capture from the environment is then mandatory and fortunately, for the considered application, solar energy can be harvested because i) the sensors are located outside the aircraft ii) for security and simplicity reasons most flight tests are done at daylight. It is worth mentioning that minimum energy storage is here still required for two reasons: first to accommodate for transient power surges from the load exceeding the mean electrical harvested power, and then to maintain the energetic autonomy in the case of an intermittent environmental source. For our application, as illustrated later, the two effects combine. Supercapacitors, also named Ultra Capacitors (UCs), performing electrostatic storage may do the job; while being affected by extreme positive ambient temperatures similarly to most batteries, they exhibit better performance at low temperature and provide an almost infinite lifetime. Consequently, they do not need any replacement. Because of their low energy density, they are safer than batteries, and supposed to be more environment-friendly. Unfortunately, they exhibit a charge-dependent output voltage asking for a voltage regulator when used for circuit biasing, and suffer from a low maximum voltage rating (as low as 2.2V for some models tested below) related to the dielectric properties of the electrolyte.

More precisely, for supplying power to the above pressure sensors, specific requirements are to be fulfilled. First, the power supply (comprising photovoltaic cells, maximum power point tracking circuit, energy management devices and buffer storage UCs) must be both very thin not to disturb the streamline flow, and globally flexible to adapt to curvy profiles. Considering areas, flexibility main impact is on photovoltaic (PV) cells, restricting the choice to flexible cell technologies.

Then, all devices must operate at low temperature (down to -55°C) and reduced atmospheric pressure (200hPa); fortunately low temperatures have a favorable impact on PV cell yield. Conversely, references of energy buffer UCs correctly performing at such extreme temperatures and ambient pressure must be identified.

General architecture

General requirements of our application translate into the following. The flexible power supply dedicated to be bonded to the extrados of an aircraft wing (Fig. 2) must:

- use PV cells as main source of energy,
- be less than a few millimeters in thickness,
- deliver a mean electrical power of at least 2W under 48V), under modest (cloudy) illumination,
- operate between -50°C (cruise altitude) and $+85^{\circ}\text{C}$ (parking under direct sunlight), and down to 200hPa (i.e. 35,000 ft),
- incorporate an energy storage unit in order to deal with transient absence of sunlight, the targeted autonomy being 20 s,
- be capable of autonomous start-up, with the help of solar cells alone, the storage unit being empty.

Considering the above specifications, we devised the general architecture depicted in Fig. 3. The PV cells are connected to a power conditioning unit whose task is to optimize the energy transfer through Maximum Power Point Tracking (MPPT), to store the energy in the UC and to deliver a regulated output voltage. It also protects the UC from overvoltage. A blocking diode is inserted between power conditioning and UC to prevent the latter from discharging itself when photovoltaic cells are not delivering any energy.

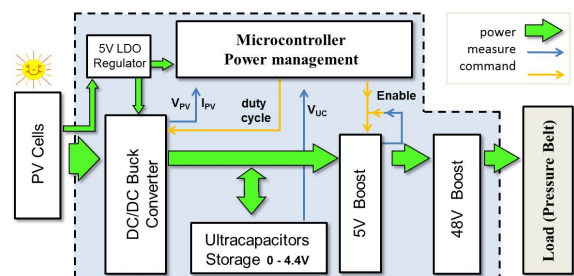


Fig. 3. General architecture of the power conditioning unit.

The UC is connected to the load through two daisy chained boost regulators. An initial requirement asked for a 5 V output, later modified for a 48 V output. To reduce delivery delay, a second boost regulator has consequently been added. Many

electronic devices, such as the microcontroller and the converters, require a bias voltage. For this purpose, a 5 volts LDO voltage regulator TPS71550 ($V_{out} = 5V$, $6V \leq V_{in} \leq 24V$) is directly connected to solar panel. Consequently, if the photovoltaic voltage falls under 6V, the Power Conditioning unit in between PV panel and UCs is cut off and, the load is powered by UCs only. This Power Conditioning unit is a DC/DC synchronous buck converter in series with a blocking Schottky diode. In a start-up phase, as long as the 5V boost regulator input voltage is below minimum operating value, Power Conditioner unit does not bias the regulator, in order to speed-up UC charge and to avoid false start-up.

Technical choices

For the solar cell testing, key points were the selection of a robust flexible PV panel exhibiting a good efficiency at low light, as the system has to power the load even in cloudy weather. We selected thin film monocrystalline Si PV cells, reaching 11% efficiency at 58 W/m^2 and 17% for Standard Test Conditions. Fig. 4 shows flexibility and main characteristics of the selected PV panel (SolbianFlex SP50-L).

Considering energy storage, we tested in climatic chambers 8 types of UCs from six different manufacturers to identify technologies compatible with our requirements. According to data sheets, the operating temperatures were ranging between $[-20, +70^\circ\text{C}]$ and $[-40, +85^\circ\text{C}]$ depending upon model. In other words, no model was initially rated for the extended range of $[-50, +85^\circ\text{C}]$. With a SP-240 4A potentiostat from BioLogic, we first submitted the devices to constant current charges and discharges in a Temptronic Thermostream climatic chamber, at temperatures between -50°C and $+100^\circ\text{C}$. Then, at -50°C only, we submitted them to an identical charge and discharge cycle, at 200hPa, in another climatic chamber (CLIMATS EX5423-TE).

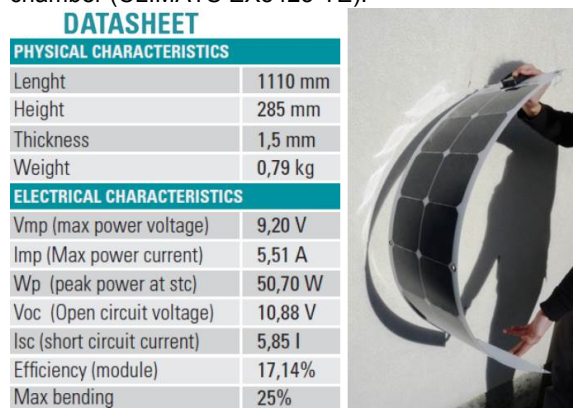


Fig. 4. Main characteristics of SolbianFlex SP50-L.

During these two sets of experiments, we plotted the $V(t)$ curves and the drift vs. temperature (see the example of Fig. 5). From the above tests we made a trade-off and identified Maxwell PC10 as an appropriate reference, also considering both thickness and capacitance per cm^2 , in order to comply with the already mentioned thickness

requirements and to minimize the area devoted to energy storage. Four PC10 were arranged in a 2S2P configuration (equivalent to 10 F total capacitance) to allow a 20 s autonomy.

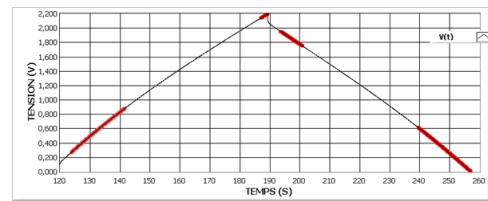


Fig. 5. Example of charge and discharge of an ultracapacitor @ $\pm 300 \text{ mA}$ respectively. The voltage drop after the peak is due to the series resistor of the UC.

We then realized a Photovoltaic Energy Harvester module (PVEH) (see Fig. 6) incorporating all devices shown in Fig. 3 except PV cells and loads. We carefully limited the thickness of the circuit, specifically that of the inductor.

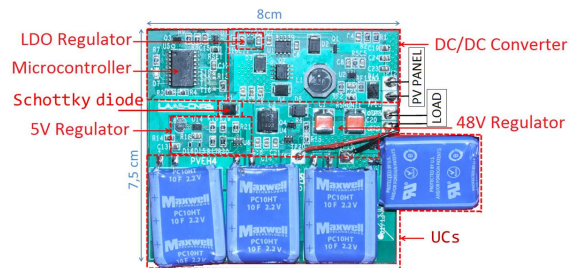


Fig. 6. PVEH board.

To deal with various atmospheric conditions, a MPPT algorithm is implemented in a PIC18F1220 microcontroller based upon fractional Open-Circuit Voltage Method with the advantage of using one sensor only. When the UCs voltage reaches almost its maximum rated value, the algorithm will move from MPPT mode to UC voltage regulation mode. A boost regulator (LT3539) is placed between the UCs and the load in order to regulate the output voltage to 5V. The input voltage range of this component is 2.3-4.4V when it supplies 2W.

We used LT3539 Shutdown pin to keep the output disabled and to allow the PV panel to first charge UCs. When the UCs terminal voltage reaches 4 V (the higher the voltage across the UCs is, the better the LT3539 efficiency is), the LT3539 is turned on by a command from the microcontroller. Then the PV panel will both power the load and charge the UCs provided the sun is shining strongly enough. If not, the UCs alone will power the load.

The 5V to 48V conversion is realized by a MAX1523 boost controller, powered by the L T3539 output, and thus is only activated when the LT3539 is on. Finally, for the bonding onto the aircraft wing, the electronic power management board together with UCs was inserted into a thin polymer fairing whose shape was designed in order to minimize aerodynamic disturbances to the airflow. Pictures of this arrangement are shown in Fig. 7. Paths for cables to the photovoltaic panel and the sensors are set up in the beveled edges of the fairing.

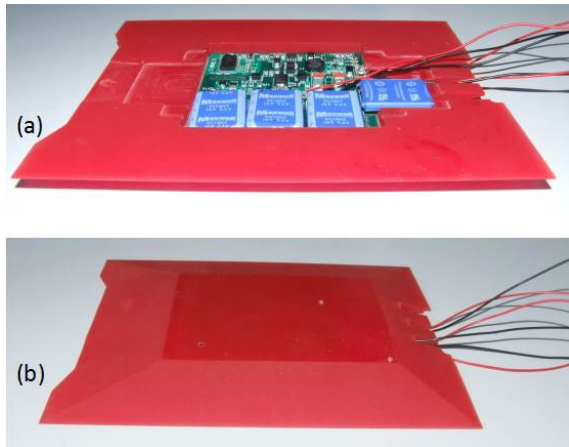


Fig. 7. (a) power management module and ultracapacitors inserted into polymer fairing (b) package as it will appear once bonded to the aircraft wing.

Experimental results

Initial ground tests confirmed that the system was supplying 2W with a solar irradiance as low as 80W/m^2 . Later, the above apparatus has been bonded on the left wing of an Airbus A321 in June 2014 in Toulouse (Fig. 8). It has then been tested under very various conditions: early take-off, heavy rain, high ground temperatures, and finally a memorable storm when the aircraft was still on parking. During a typical test (Fig. 9), altitudes were typically 2,000 and 4,000 ft with a maximum of 10,000 ft.

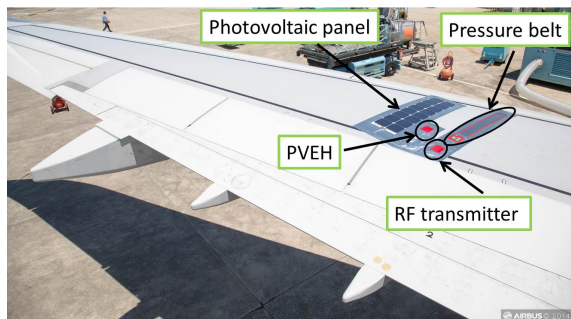


Fig. 8. Experimental apparatus bonded on Airbus A321 test aircraft.

Fig. 10 shows results obtained for a flight between 6.40 am and 9.40 am (French time), the 27th of June 2014 (sunrise took place at 5.59 am). During the first part of this flight, diffuse light was still low and when the PV was in the aircraft own shadow it could not convert enough energy and measurement stopped (see Fig. 10) roughly after 20 s as expected. Later, measurement was continuous as diffuse light was larger and storage large enough.

Conclusion

Improvement of the system is in progress to decrease PV panel area through the use of a new technology. Also the co-location of energy management and signal processing / wireless transmitter is under study. Nonetheless, first results are encouraging (all the data have been correctly transmitted as soon as adequate irradiance and

storage level were available) and show the possibility to deploy WSN for temporary test rig.



Fig. 9. Experimental apparatus during flight.

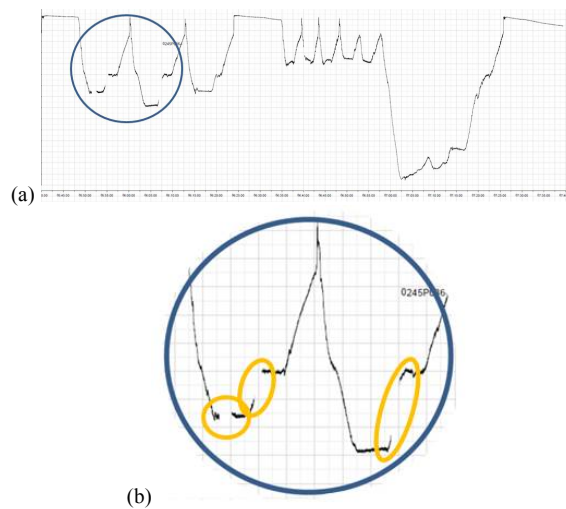


Fig. 10. (a) recording of one of the sensors between 7.40 and 9.40 pm and (b) zoom showing early gaps in measurement due to a shadow effect and insufficient energy storage.

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