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Review on energy harvesting for structural health monitoring in aeronautical applications

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ABSTRACT

This paper reviews recent developments in energy harvesting technologies for structural health monitoring (SHM) in aeronautical applications. Aeronautical industries show a great deal of interest in obtaining technologies that can be used to monitor the health of machinery and structures. In particular, the need for self-sufficient monitoring of structures has been ever-increasing in recent years. Autonomous SHM systems typically include embedded sensors, and elements for data acquisition, wireless communication, and energy harvesting. Among all of these components, this paper focuses on energy harvesting technologies. Actually, low-power sensors and wireless communication components are used in newer SHM systems, and a number of researchers have recently investigated such techniques to extract energy from the local environment to power these stand-alone systems. The first part of the paper is dedicated to the different energy sources available in aeronautical applications, i.e., for airplanes and helicopters. The second part gives a presentation of the various devices developed for converting ambient energy into electric power. The last part is dedicated to a comparison of the different technologies and the future development of energy harvesting for aeronautical applications.

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1. Introduction

SHM for aerospace applications offers a truly viable solution for full-coverage continuous monitoring of aircraft (i.e., airplanes, helicopters) structures or security components (i.e., bearings, rods, etc.) [1]. In essence, it leads to optimized structures in critical areas, drastically alters maintenance regimes and minimizes downtime, whilst also improving reliability and safety. Furthermore, the implementation of an SHM system at the design stage results in an enhanced aircraft performance, lower fuel consumption, thus making it possible to reduce the weight and running costs of an aircraft [1].

To summarize, future applications for autonomous sensors in aeronauticals may be divided into following three groups [2–5]:

1. Maintenance support
2. Aircrew aid
3. Flight test instrumentation

Maintenance support aims at enhancing the effectiveness of all maintenance activities throughout the life of an aircraft. Actually, the maintenance of an aircraft is performed in a scheduled manner. For instance, in the company Airbus [3], three different checks, i.e., A, B, and C, are scheduled at fixed intervals, depending on the type of aircraft. A typical interval for an A check is about 300–700 flight hours, a B check is performed every five-six months, and a C check after 18 months at the latest.

Whereas daily overnight inspection includes visual examinations of the aircraft, the checks mentioned above are accompanied by the dismantling of the cabin interior and the dismounting of fairings or the use of endoscopes to monitor inaccessible areas. Crack or damage detection is also performed, e.g., by using ultrasonic techniques, and all lubricants or other fluids are changed. Obviously, these checks require a lot of manpower and, in addition, the aircraft is grounded. A complete C check takes about five days depending on the aircraft [3].

It is therefore easy to understand that the benefit of a self-powered system is twofold. First, it constitutes an efficient tool for improving maintenance activities, and second, it can be used as a transition from a programmed maintenance to a predictive one [2]. Hence, self-powered systems lead to an increased aircraft service life and thus reduced maintenance costs. Also, the efficiency can be improved by using autonomous sensors located at remote or inaccessible areas. In this case, measurements are easily carried out without dismantling any modules. Predictive maintenance can be performed with integrated self-sufficient network sensors aiming at collecting data to calculate the state of the monitored components [2].

An automatic aircrew aid system is useful to alleviate the workload and reduce the energy consumption. Harvesting body heat is just one example: instead of producing energy, it would simply collect energy from a passenger seat, and redirect it to power certain aircraft functions – such as the cabin lights, the passenger status monitoring, the security alarm. However, the weight of "aircraft equipment" is a key factor and must match the airline design and should not disturb the passengers.

Another objective of self-powered systems is flight test instrumentation. This application field requires flexible sensors that considerably depend on the quantity and type of measurements [6,7]. All these application areas constitute a promising future market, but a number of challenges must still be resolved, as illustrated in the following sections.

2. Energy sources in airplanes and helicopters

Modern aircraft comprise a multitude of energy sources that can be accessed with energy harvesting technologies: temperature differences, temperature changes, vibrations, strain, ambient light, pressure changes, electrostatic charges, etc. However, not all sources hold sufficient potential to provide enough power to a sensor system. The most critical parameter for comparing these technologies in the scope of aircraft applicability is their power-to-weight ratio (per flight cycle) [4]. Another important criterion is the reliability of these devices. Sources that seem most likely to meet the sector constraints are thermal and vibrational energies [2].

2.1. Mechanical sources

Both internal and external sources of vibration exist in aircraft. The primary internal source is the propulsion system. In helicopters and propeller-driven aircraft, vibration is generated at very distinct frequencies associated with the rotor speed and blade passage frequency. The rotor speeds for helicopters can result in relatively low vibrations, usually less than 10 Hz. The blade passage frequencies related to three- and four-bladed helicopters can fall below 40 Hz. Other propeller-driven aircraft have higher rotor frequencies. For instance, the Navy E-2C Hawkeye has a rotor speed of 18.4 Hz [8]. With four blades, the passage frequency can lead to four times the rotor speed, i.e., 73.6 Hz [8].

Smith et al. measured the acceleration of 0.8 m/s^2 at 73.6 Hz on a flight officer seat during E-2 Hawkeye operations [9]. All components experienced significant vibration from the main rotor and this dominated the low frequency spectrum depending on the positions in the aircraft. For example, components situated at or near the aircraft tail received principal harmonics of the tail rotor. On the other hand, components located adjacent to the engines and gearboxes obtained additional harmonics from the engine, shaft, and gearbox meshing frequencies.

Dickson measured an acceleration of 3.5 g at 80 Hz in a gearbox of an AH-64A helicopter [8]. Currently, the majority of commercial airplanes use jet engines but even the latest advanced design and technology have not been able to counter the age-old challenge of noise and vibration. The vibration produced by the jet engine is typically included in the frequency bandwidth range between 20 Hz and 500 Hz, under a maximum acceleration of 3 g [10]. It is common practice to segregate the aircraft into regions and assume that the vibration amplitudes are similar for all equipment positioned in that region. The most commonly defined regions are:

- Fuselage – the vibration is dominated by harmonics of the blade passing frequency of the main rotor.
- Avionics bay – similar to the fuselage but vibration-isolated mounts are designed to reduce the rotor's vibration-induced vibration amplitudes.
- On or near the engines – additional sinusoidal harmonics induced through engine and gearbox harmonics and meshing frequencies.