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Feasibility of a fully autonomous wireless monitoring system for a wind turbine blade

O.O. Esu [a], S.D. Lloyd [b], J.A. Flint [a, *], S.J. Watson [b]

[a] Wireless Communications Research Group, Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Ashby Road, Loughborough, Leicestershire, LE11 3TU, UK

[b] Centre for Renewable Energy Systems Technology, Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Ashby Road, Loughborough, Leicestershire, LE11 3TU, UK

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A B S T R A C T

Condition monitoring (CM) of wind turbine blades has significant benefits for wind farm operators and insurers alike. Blades present a particular challenge in terms of operations and maintenance: the wide range of materials used in their construction makes it difficult to predict lifetimes; loading is stochastic and highly variable; and access can be problematic due to the remote locations where turbines are frequently located, particularly for offshore installations. Whilst previous works have indicated that Micro Electromechanical Systems (MEMS) accelerometers are viable devices for measuring the vibrations from which diagnostic information can be derived, thus far there has been no analysis of how such a system would be powered. This paper considers the power requirement of a self-powered blade-tip autonomous system and how those requirements can be met. The radio link budget is derived for the system and the average power requirement assessed. Following this, energy harvesting methods such as photovoltaics, vibration, thermal and radio frequency (RF) are explored. Energy storage techniques and energy regulation for the autonomous system are assessed along with their relative merits. It is concluded that vibration (piezoelectric) energy harvesting combined with lithium-ion batteries are suitable selections for such a system.

1. Introduction

Energy harvesting is the process by which low-density ambient energy is captured, converted and stored, if necessary, to provide low-power generation for powering electronic devices [1,2]. Solar, thermal, mechanical and electromagnetic radiation are the most common sources for harvesting electrical energy from the environment. Not all of these sources, such as solar and thermal energy, are available all the time so it is necessary to incorporate a storage device to power the system for continuous operation. The introduction of a storage element has the disadvantage that devices such as batteries have a limited lifespan, so it is necessary to take this into account if the system is to be fitted for the lifetime of a mechanical component such as a wind turbine blade.

There has been renewed interest in power harvesting in recent years which has been driven by advances in transducer technology, improvements in storage devices and the ready availability of custom integrated circuits (ICs) for power management. The devices often benefit from a miniature size, ease of installation, flexibility, suitability for retrofitting and their very low cost. The compact nature of these devices and lack of dependence on a permanent power source make them good candidates for installation in remote locations and indeed in places where it would not normally be considered feasible to install an autonomous system. The present paper presents a technical analysis of a fully autonomous monitoring system placed right on (or within) a wind turbine blade near to the tip for the purpose of monitoring its condition [3,4]. Whereas previous work has established the feasibility of using low cost MEMS accelerometers to assess the modal properties in experimental studies of small to medium sized turbine blades [5,6], the present paper focuses on the issue of providing a power source to such a system and its design parameters. Another important contribution of the present paper over previous works is consideration of the detailed requirements of such a system and

* Corresponding author.
E-mail addresses: O.O.Esu@lboro.ac.uk (O.O. Esu), S.D.Lloyd-10@student.lboro.ac.uk (S.D. Lloyd), james.flint@ieee.org (J.A. Flint), S.J.Watson@lboro.ac.uk (S.J. Watson).

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providing calculations of the radio link budget. The link budget has a close relationship with the power requirement as it is a major source of energy loss from the autonomous system. The problem is challenging as the radio power required varies as the machine turns and there are potential power savings that can be achieved by controlling the transmit power in sympathy with the transmitter's position. This problem is not presently addressed in the literature.

Condition monitoring (CM), which is the continual sensing of parameters affecting machine operation to provide early warning of reliability issues, is well understood for large, constant speed rotating machines but has only recently been investigated for wind turbines. Condition monitoring of wind turbines presents a substantial engineering challenge due to the presence of both low speed and high speed rotating shafts, as well as highly dynamic vibrations in torque and speed [7–12]. Vibration-based condition monitoring techniques are the most widely employed and can be used to monitor components such as the gearbox, generator, bearing and blades. Vibration-based systems are based on the principle of relating the resonant properties of a structure to its physical properties. Changes in the physical properties of a structure (mass, stiffness and damping properties) can cause changes in resonant properties of that structure such as the natural frequency, modal damping and mode shape [5,6,13–19]. A number of different techniques have been proposed for the monitoring of wind turbine blades [20], however, this paper focuses on the design parameters and feasibility of an autonomous system that could be used for modal analysis.

Specifically, this paper considers the issues surrounding the installation a wireless monitoring system within a wind turbine blade, which is fully self-contained, self-powered and able to transmit data concerning the condition of the blade to a base station on the ground. Such a system has various technical challenges, such as the provision of a power supply which can outlast the service life of the blade and the availability and location of sensors such as accelerometers that can be deployed within the structure to measure the various properties of the blade during operation. In addition to the power and electronic requirements, a strategy for monitoring and signal processing the received data is also worthy of consideration. The present paper covers the fundamental power requirements of such a system and the feasibility of providing this power using energy harvesting devices located within or on a blade. It explores the energy requirements necessary to acquire frequency domain statistics such as Fast Fourier Transforms (FFTs) and transmit this vibration data. Section 2 describes the autonomous low-cost wireless system components and the operation. Section 3 describes the power requirements of the system and the radio link budget, Section 4 describes the energy sources considered for powering the system, Section 5 provides analysis of some commercially available energy harvesters and finally Section 6 offers conclusions and recommendations.

2. Description of the autonomous system

Esu et al. [5,6,16] describe the use of MEMS accelerometers for detecting the vibrations of wind turbine blades. The widespread use of MEMS accelerometers in smartphones [21] and for airbag deployment in the automotive industries has decreased their cost and made them readily available. The CM system described in this paper capitalises on these merits. The autonomous wireless CM system comprises of a number of small (dimension: 4 mm × 4 mm × 1.45 mm) surface micro-machined capacitive ADXL335 [22] MEMS accelerometers that measure acceleration in 3-axes with a full-scale range of ±3 g (where 1 g = 9.81 ms^{-2}) and have a power consumption of 1 mW when supplied with a nominal voltage of 3 V [23–28].

The accelerometers detect and measure the vibration of the blade to which they are affixed and the measured data are logged using a 16-bit high performance dsPIC33F Microchip [29] digital signal microcontroller. The Microchip dsPIC33FJ128MC802 microcontroller [29] was chosen because of its low power consumption, digital signal processing capabilities and its operating voltage of 3.3 V. These devices also provide a real-time response, have a flash memory of up to 128 KB and a CPU speed of 40 MIPS. They perform well in harsh environments and can withstand vibrations [30]. The microcontroller has a watchdog timer and extensive power management functionality with idle, sleep and doze modes with fast wake-up features at low current consumptions (~nA). These features or equivalents are also available in devices from other manufacturers, however the one chosen is typical of a class of low power microcontrollers with signal processing capability.

The microcontroller samples the measured data and performs a FFT on them ready for wireless transmission. A wireless RF transmitter module [31] which has a current consumption of 8 mA at 3 V is connected to the microcontroller and the transformed data, composed of peak frequency and amplitude, are transmitted to a remote ground-based receiver and computer, where performance plots are displayed to indicate the state of health of the wind turbine blade. The desired specification for the system is to display a spectrum from 0 to 500 Hz. Analysing vibration data in the frequency domain provides a useful indication of the blade health and enables the identification of impending failures from its characteristic vibration signature [5,32–35].

The microcontroller is able to selectively power the RF circuits according to the accumulated charge on the systems storage unit by integrating the voltage applied to the storage unit with respect to time whilst in a low power mode. The energy regulator is able to signal to the microcontroller when the power supply is good from the energy harvester and in addition the microcontroller is able to manage the operation of the regulator and can shut it down in the case that the storage unit is full. Thus the function of the system can be fully managed by the microcontroller, which can also choose to perform computationally intensive signal processing only when adequate energy is available in the storage unit. Fig. 1 illustrates the architecture of the condition monitoring device. After measuring vibrations and transmitting the data to the base station, the device goes into sleep mode until the next measurement to save power. In sleep mode, the current consumption of the microcontroller is very low since the microcontroller only needs to monitor the state of charge on the storage unit.

3. Predicted power consumption

3.1. Radio channel link budget

Consider the system geometry shown in Fig. 2.

The power at the ground based receiver is thus:

$$P_R = P_T + G_T - L_T - L_{FS} - L_M + G_R - L_R \quad (1)$$

where P_R is the received power in dBm. G_T and G_R are the antenna gains of the transmitter and receiver in dBi, L_R and L_M are loss factors in dB for miscellaneous mechanisms such a polarization mismatch between transmitter and receiver.

The term L_{FS} is the free space radiation loss associated with the radio channel and is a function of transmit frequency, f and the distance of the link, d in m. If the speed of radio propagation in air is $c \approx 3 \times 10^8$ m/s then the loss is given by Friis' formula: