Wireless Sensor Network for Helicopter Rotor Blade Vibration Monitoring: Requirements Definition and Technological Aspects

SANCHEZ RAMIREZ Andrea[1, a], DAS Kallol[2, b], LOENDERSLOOT Richard[1, c], TINGA Tiedo[1, 3, d] and HAVINGA Paul[2, e]

[1]**Chair of Dynamics Based Maintenance, University of Twente, The Netherlands**

[2]Pervasive Systems Group, University of Twente, The Netherlands

[3]Faculty of Military Sciences, Netherlands Defense Academy, The Netherlands.

[a]a.sanchezramirez@utwente.nl, [b]k.das@utwente.nl, [c]r.loendersloot@utwente.nl, [d]t.tinga@utwente.nl, [e]p.j.m.havinga@utwente.nl

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Abstract. The main rotor accounts for the largest vibration source for a helicopter fuselage and its components. However, accurate blade monitoring has been limited due to the practical restrictions on instrumenting rotating blades. The use of Wireless Sensor Networks (WSNs) for real time vibration monitoring promises to deliver a significant contribution to rotor performance monitoring and blade damage identification. This paper discusses the main technological challenges for wireless sensor networks for vibration monitoring on helicopter rotor blades. The first part introduces the context of vibration monitoring on helicopters. Secondly, an overview of the main failure modes for rotor and blades is presented. Based on the requirements for failure modes monitoring, a proposition for a multipurpose sensor network is presented. The network aims to monitor rotor performance, blade integrity and damage accumulation at three different scales referred to as macro layer, meso layer and micro layer. The final part presents the requirements for WSNs design in relation with sensing, processing, communication, actuation and power supply.

1. Introduction

The reasons for vibration monitoring on helicopters have changed throughout time. Initially, improving safety was pointed out as the main objective for vibration levels surveillance [1]. Subsequently reducing maintenance costs while maximizing availability pushed for more assertive vibration data treatment than only establishing safe operating levels [2]. Current trends on helicopter management point towards the integration of safety, usage and maintenance requirements, embodied as in Health and Usage Monitoring Systems (HUMS) [3,4].

Parallel to the motives behind vibration monitoring, the platforms for data acquisition and analysis have also evolved, ranging from Flight Data Acquisition (FDA), Cockpit Voice and Flight Data Recorder (CVFDR) to Vibration Health Monitoring Systems (VHM) [2]. Current VHM systems are designed for comprehensive vibration signal acquisition and analysis correlation with other maintenance and operational parameters. The intended monitoring capability of the VHM systems covers engines, gearboxes, accessories and the main and tail rotors. Current VHM systems follow a Digital Signal Processor (DSP) based design [1-3], which provides measurement and on-board processing capability to allow diagnostic of common failure modes. Other functions include correlation of the vibration profile with the flight regime, trend monitoring, event detection and outputs for rotor blade adjustments during maintenance.

Although the main rotor is the principal source for the vibrations in helicopters [Fig. 1], the existing vibration monitoring systems focus on other locations than the rotor itself. The reasons for this exclusion are the inconveniences for locating, powering and communicating with transducers on

rotating blades. Still, rotor diagnostics is supported by lag measurements using optical trackers and by vibration measurements at the swashplate bearing [5,6]. Fortunately, developments on WSNs bring the possibility to access traditionally hard-to-reach locations and therefore contribute with direct blade vibration monitoring.
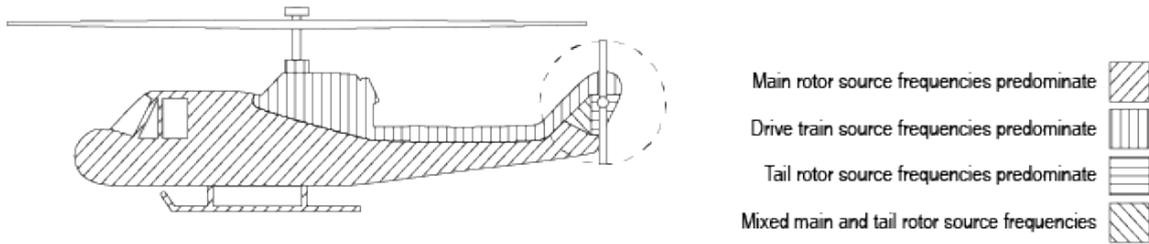

Figure 1. Helicoper Vibration Zones [7]

Summarizing, existing condition monitoring systems for helicopter monitoring include a combination of complex aspects such as distributed sensing, processing and failure mode correlation. The use of WSNs complements existing vibration monitoring systems by including on-blade sensing. The next section shows the correlation between the requirements for vibration monitoring based on the most relevant failure modes.

2. Rotor Failure Modes

Helicopter rotors exhibit a wide variety of failure modes. These are not only present at different sections of the rotor, but they also can progress at different rates and lead to distinct effects. As an example, aerodynamic imbalance leads to significant vibration levels during operation while local cracks do not. On the other hand, even superficial cracks, if unattended, can develop into structural cracks and threaten the entire blade structure. Given such diversity on failure modes, helicopter maintainers apply a wide range of methods for condition monitoring. Some of these techniques are employed during flight such as vibration analysis, blade tracking and performance monitoring; others are executed at the flight line or in the workshop such as visual inspections, X-rays and other Non-Destructive Techniques (NDTs).

Table 1. Sensor Network Main Functions.

Rotor Performance (Macro)	Blade Integrity (Meso)	Local Damage (Micro)
Aerodynamic imbalance Wrong pitch control	Mass imbalance Structural cracks Foreign object damage	Superficial cracks Matrix degradation Delamination

Table 1 presents a classification of failure modes per domain, namely rotor, blade and blade section, each representing different length scales. Each category can be associated with a specific function to be fulfilled by a sensor network: *rotor performance monitoring, blade integrity check, and local damage monitoring*.

3. Multi Scale Approach

Autonomous and distributed sensing are required capabilities for dealing with network functions. However, finding the balance between the node autonomy and the network cooperation is a main issue for WSNs design. The description of the thee scales proposed for the WSN is shown as follows.

3.1 Rotor performance (Macro layer). This stage, referred here as *macro layer*, aims to evaluate the general aspects of rotor vibration during flight. Several studies demonstrate the vibration profile sensitivity towards damage [8-10]. Therefore selected sensors are deployed for monitoring key blade parameters such as root strain, tip displacements and blade torsion.

The flight regime dependence of the vibration profile poses additional challenges for the rotor performance evaluation. Although HUMS already approaches this problem by establishing operational bands, WSN collaborative capabilities can provide additional features for solving it. The proposed strategy is based on the comparison of *simultaneously* measured quantities within and between the blades. Transfer functions defined by locations within the same blades are expected to be operational invariant, e.g. the ratio between root strain to tip displacement. The comparison between different blades can also support the identification of troublesome blades by spotting differences in their vibration profile.

3.2 Blade Integrity (Meso Layer). Blade integrity is assessed at the *meso layer*. The purpose at this scale is to provide additional diagnostics on the blade's integrity by using a denser network. The term blade integrity refers to considerable changes of mass or stiffness distribution that affect the entire blade function, e.g. mass imbalance.

Quantification of the mass and stiffness distributions is possible by means of structural health monitoring methods (SHM) such as modal based algorithms. Transfer functions similar to those proposed at the macro layer constitute the base for these algorithms. Once the modal parameters are known, several methods for damage identification can be used, depending on the particular failure mode of interest. Examples are methods based on natural frequencies, mode shapes and their derivatives and modal strain energy [11-15].

The most common method to estimate the modal parameters is the Experimental Modal Analysis (EMA). However this requires controlled excitations which are unpractical for large structures. An alternative is to use environmental excitations as in the case of Operational Modal Analysis (OMA). By not incorporating actuation, the power requirements on the sensor nodes decreases. However OMA requires some additional signal processing methods to estimate the modal parameters, such as harmonic removal algorithms. As a consequence, OMA imposes the need for computational intensive algorithms that are not feasible to be performed at the wireless nodes [16-18].

3.3 Damage Identification (Micro Layer). The micro layer focuses on the blade's most relevant local damages, such as surface cracks, matrix degradation, delamination and coating erosion. These defects do not necessary affect the performance of the blade, but unsupervised can lead to major structural damage. Helicopter maintainers already employ several NDTs methods [19]. Several of these interrogation methods that require an active approach can be performed using embedded sensors and actuators. However their fully implementation on autonomous WSNs is restricted by the need for controlled active excitation, which implies high power consumption and more complex electronics.

Alternatively, passive SHM methods can be implemented more easily within a WSNs since these do not need active excitation. The Modal Strain Energy Damage Index (MSE-DI) algorithm has been pointed out as sensitive for discontinuities on the modal shape, originating from a local stiffness loss and hence directly related to the damage [14-15]. An advantage of the MSE-DI method that the number of sensors can be optimized for the selected set of modes, however a high number of modes are required for local damage identification.

Table 2. Characteristics of the multipurpose WSNs for helicopter rotor

	Macro	*Meso*	*Micro*
Domain	Rotor	Blade	Blade section
Function	Rotor performance	Blade integrity	Local damage
Conditions during measurements	Flight Noisy environment	Ground rotation	Ground.
Method	- Spectral analysis, - Correlation	- Modal extraction OMA - natural frequencies shift, modal shape, energy, strain	- Based on passive SHM. MSE-DI - Based on NDT and active SHM
Number of nodes per blade	Few (<5)	Medium (20-50)	Medium (20-50)
Actuation required	No	No	MSE-DI : No Other methods yes.

Table 2 summarizes the main characteristics of the multi scale WSN for helicopter rotor blade monitoring. Despite the differences exhibited by the proposed layers, some characteristics, such as the need for distributed sensing, high data resolution and high data throughput, are also common for the three layers. These desired features have direct incidence on WSNs requirements regarding data quality, synchronization and local processing. The following section introduces the main aspects of WSNs and their relation with the described WHAT? in line with helicopter blade vibration monitoring application.

4. Wireless Sensor Network Function Analysis

A Wireless Sensor Network (WSN) consists of a large number of sensors and actuators, which are typically tiny, low-cost, low-powered radio devices dedicated to performing certain functions such as collecting various environmental data and transmitting them to central processing units [20]. Although WSN are already employed on military, environmental, and structural monitoring applications [21], its application in rotorcraft transportation is still limited. WSNs display four major functions: *sensing*, *local processing*, *communication* and *actuation* as discussed in the following sections.

4.1 Sensing: Vibration monitoring on helicopter environments poses important requirements on WSNs regarding sensing. High signal to noise ratio becomes relevant when noisy environments are expected, as in the case of complex aerodynamic phenomena during flight. Furthermore for the meso layer, signal processing algorithms such as harmonic removal and modes extraction require high signal quality, f.i. signal to noise ratio. At the micro layer, the choice of sampling rate is strongly linked to the interrogation methods for local damage detection. Although high signal quality and sampling rates can be achieved by appropriate memory, bit length and processor speed, these reflect immediately in the power supply demands at the node.

Sensor type selection and conditioning circuit implementation require special attention for realization of the autonomous nodes on the helicopter blades. Sensor selection includes the choice of transducer type and conditioning circuit and it is based on sensitivity, frequency range, polarization and signal amplification requirements. Mechanically, the integration of the node with the blade has to fulfil tight physical constraints for effective integration on the helicopter blade [25].

4.2 Local processing: The data collected by the sensors can be processed on the node locally or transmitted directly to the central processing unit. However the line between processing and communicating is difficult to set off. Although communication is traditionally more power

demanding compared to sensing and processing, increasing complexity on the local processing also involves more demanding electronics and higher power supply requirements.

Several degrees of local processing are expected for the multi scale WSN ranging from basic signal processing operations such as averaging, peak detection and spectral decomposition. Improving data quality is achieved by the cleansing, filtering and classification, although this calls for memory at the processor. Higher complexity is expected by performing transfer functions as suggested for the macro layer and modal based methods for the meso layer. In conclusion, the appropriate level of processing and communication becomes a pivotal discussion for WSNs design.

4.3 Communication: The reliability, robustness and efficiency of the communication between the nodes and with the control centre is a crucial aspect of WSNs. The coordination of the different aspects of the communication is done by the *communication protocol* that refers to the common *code of conduct* of the nodes or communication rules of the nodes. Protocols are classified within standards, which share general characteristics such as over-the-air modulation techniques, time synchronization algorithms, broadcasted frequencies, etc. The capabilities and limitations of some existing wireless sensor network standards are analysed in Zand et al. [23]. From the communication aspect, the multipurpose WSN imposes special requirements for the protocol design as explained in the following subsections.

4.3.1 Synchronization: Synchronization becomes critical when parallel measurements for further processing of correlations and transfer functions. The synchronization requirements are based on the measurement sampling frequency and the number of sensors to be matched. At the node, synchronization depends on the internal clock and on the protocol. For synchronized measurements, time division multiple access (TDMA) based protocols supports shared bandwidth among nodes by employing strategies based on time division or *slots* of the communication time frame (Figure 2). This protocol type allows the transmitter to use only a predefined amount of slots for data transmitting [22].

4.3.2 Throughput: The amount of data communicated within a given period of time is known as throughput. For transmitting the time signal, the throughput depends linearly on the sampling frequency, the measurement length and the precision required. However throughput is reduced by local processing as previously discussed.

4.3.3 Reliability: Communication through wireless media implies by default larger risks of bit losses. Furthermore, the helicopter environment imposes additional challenges due to possible reflections of metal parts and due to the rotation of the blades. However the proposed network includes certain advantages for the communication systems, such as predefined sensor location and relatively short transmitting range (<10m).

The impact of these aspects on the WSNs communication system (antennas, receptors, transmitters) can be addressed by physical aspects of the communication link, such as tuning antenna directivity, enhancing transmitting power, and employing robust receptors, etc. Besides these physical aspects, the communication protocol can contribute with reliability by different methods [23-24]. Nonetheless, both physical and protocol related procedures increase the processing load and therefore energy consumption. A less power demanding alternatively is node clustering, which can improve communication reliability by centralizing the communication to only one radio – usually stronger – for transmitting data from a number of sensors.

For blade monitoring, communication delay has not been identified as a critical requirement since there is no need for real time feedback for control purposes. After the data is collected and processed, the communication to the control can be performed in suitable time frames in a way that transmission is conditioned only when available power is sufficient.
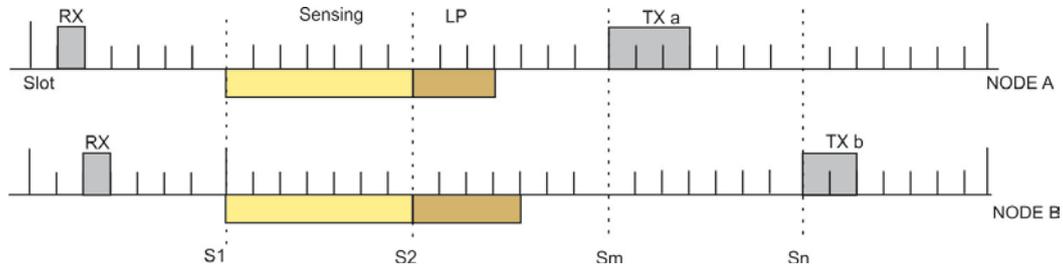

Figure 2. Schematic representation of wireless vibration monitoring with local processing

In summary, an energy efficient communication protocol for vibration monitoring for helicopter rotor blades must consider high throughput, synchronization and reliability. Other aspects such as latency and duty cycle can be tuned according to available power. Figure 2 presents schematically the communication and the on node measurement and processing process. All nodes of the sensor share the same time counting by having synchronized clocks and equal duration of slots. Each node enters the reception mode (RX) for precise instructions about the sensing tasks. At a time indicated on the received message (S1), all the involved nodes undertake the measurement tasks simultaneously. Once the measurement is concluded (S2), each node conducts the necessary local processing (LP) activities. Note that the amount of data is reduced by local processing. Communication of the processed data is transmitted (TX) one node at the time (Sm, Sn) based on the available power. Communication loss is depicted as the shorter length in the TXb compared to TXa, due to some possible package loss.

4.4 Actuation: Based on the signals acquired and the local processing algorithms, some WSNs include an actuation function for the nodes to perform additional tasks. A typical example is the alarm activation on fire detection networks. For the case of helicopter blades, actuation is expected for the use of active methods of interrogation for local damage detection at the micro level. The feasibility of using the same kind of transducers for sensing and actuation, as in the case of piezoelectric materials enables the choice of an active approach. However power requirements imposes limitations to this approach when harvested energy is the only power supply.

5. Power Availability for Autonomous WSNs

Power restrictions have been already identified as a critical factor for the different WSNs functions. Therefore power harvesting blades augmented with piezo patches can be selected as means to provide power to the WSN [25]. The harvester strategy consist of deploying piezoelectric patches across the blade which extract power from the strain cycles experienced during one rotation of the blade. The expected strain levels define the characteristics of the matrix material where the piezo elements are embedded in. Preliminary results seem suitable for powering electronic components, however the efficiency issues have to be further addressed. To circumvent the power restrictions some options such as defining sensible duty cycles for the sensing and wireless communication can be implemented.

6. Summary and Future Work

Vibration monitoring directly at the helicopter rotor blades presents an important advancement in health and usage monitoring systems. The autonomous and distributed sensing characteristics of Wireless Sensor Networks are to be used as main drivers for supporting this leap in monitoring systems. Two converging discussions about the failure modes based requirements on and the technological aspects of WSNs have been presented. From the application side, the monitoring system is called for diagnostic strategies for a) rotor performance, b) blade integrity and c) local damage monitoring. On the technological implementation side, the most relevant attributes for the WSN design have been targeted as (i) adequate distributed diagnostic algorithms for blade interrogation, (ii) efficient electronics for processing, sensing and harvesting and, (iii) suitable communication protocols for synchronized sensing. Future research considers a systematic analysis for both function (a-c) and technologic implementation (i-iii) aspects as a methodology for designing WSN for Helicopter Rotor Blades Vibration Monitoring.

Experimental work for advancing on the practicalities of using wireless sensors for vibration monitoring is planned. A beam like structure is chosen for further interrogation following the guidelines of the macro and meso layers. This contributes to defining the requirements for sensing, local processing, energy harvesting and wireless communication on a quantifiable manner. The conclusions of lab experiments are expected to be replicated on an actual helicopter blade. Numerical models of helicopter blade motion and suitable methods for WSN are under development.

References

[1] CAP 753, Helicopter Vibration Health Monitoring (VHM), Guidance Material for Operators Utilising VHM in Rotor and Rotor Drive Systems of Helicopters, TSO on behalf of the UK Civil Aviation Authority, ISBN: 978 0 11792 733 9, August 2012

[2] J.L. Brooks, Smiths Industries Flight Data/Cockpit Voice Recorders, International Symposium on Transportation Recorders, Virginia, USA, 1999

[3] J. Zakrajsek, P. Dempsey, E. Huff et al., Rotorcraft Health Management Issues and Challenges. NASA. Ames Research Center. *First International Forum on Integrated System Health Engineering and Management in Aerospace*; USA. 2005

[4] H. Morel. H., Viniacourt, F. Hoffman, Assessment of Anomaly detection and diagnosis applied to EuroHUMS data for maintenance alleviation. *ERF 2011*, Amsterdam. The Netherlands. 2011

[5] Information on http://www51.honeywell.com/aero/common/documents/FasTrak_Brochure.pdf

[6] E. Pryputniewicz, G. Flemming, R. Pryputniewicz. Experimental Characterization of Vibrations of a NASA Active Twist Rotor Blade. NASA Langley Research Center. IMAC-XXII. 2004.

[7] Department of Defense Test Method Standard for Enivormental Engineering Considerations and Laboratory Tests. MIL-STD-810. 2000.

[8] K. Kim., Analytical Investigation into the Helicopter Vibration Resulting from Main Rotor Blade (MRB) Ballistic Damage. ARL-TR-1985.; 41 pages. 1999

[9] J. Fries, Black Hawk Helicopter Vibration Analysis Due to Main Rotor Damage, Directional Constituents of the Resultant Vibrations. ARL-TR-2442 ; 27 pages. 2001

[10] K. Kim, Analytical Calculation of Helicopter Main Rotor Blade Flight Loads in Hover and Forward Flight. ARL-TR-3180; 24 pages. 2004

[11] C.R. Farrar. D.A. Jauregui, Comparative study of damage identification algorithms applied to a bridge: I. Experiment, Smart Materials and Structures, 7:704-719, 1998

[12] A. Alvandi, C. Cremona, Assessment of Vibration-based Damage Identification Techniques. Journal of Sound and Vibration, 292(1-2):179–202, 2006

[13] J. Humar, A. Bagchi, H, Xu, Performance of Vibration-based Techniques for the Identification of Structural Damage, Structural Health Monitoring, 5(3):215–241, 2006

 [14] N. Stubbs, C.R. Farrar, Field Verification of a Nondestructive Damage Localization and Severity Estimation Algorithm, In: Proceedings of the 13th International Modal Analysis Conference, 1995.

[15] R. Loendersloot, T.H. Ooijevaar, L. Warnet, A. de Boer, R. Akkerman, Vibration Based Structural Health Monitoring and the Modal Strain Energy Damage Index Algorithm Applied to a Composite T–Beam, In: Vibration and Structural Acoustics Analysis: Current Research and Related Technologies, Editors: C.M.A. Vasques and J.D. Rodrigues, Springer Netherlands, 2011, p:121-150

[16] S. Manzato et al. A review of harmonic removal methods for improved Operational Modal Analysis of Wind Turbines. ISMA 2012-746. Leuven. 2012.

[17] C. Grappasonni et al,. Dynamic identification of helicopter structures using operational modal analysis methods in the presence of harmonic loading. ISMA 2012-363. Leuven. 2012.

[18] B. Peeters., El-kafafy. M., Guillaume. P., The new PolyMAX Plus method: Confident Modal parameter estimation even in very noisy cases. ISMA 2012-850. Leuven. 2012.

[19] M. Balasko, G. Endroczi, L. Horvath. Application of Combined NDT Methods to Study the Helicopter Rotor Blades. MTA KFKI Atomic Energy Research Institute, H-1121 Budapest Konkoly Thege-u 29-33.

[20]J.P. Lynch, K. Loh. A Summary Review of Wireless Sensors and Sensor Networks for Stuctural Health Monitoring. Shock and Vibration Digest. Vol 38. No. 2., 2006. Pafes91-128.

[21] V. Gungor, G.P. Hanke. Industrial Wireless Sensor Networks: Challenges, Design Principles and Technical Approaches.

[22] British Standards Institute. Industrial Communication Networks-Fieldbus Specifications, WirelessHART Communication Network and Communication Profile, 1.0 ed.; IEC/PAS 62591; 2009.

[23] P. Zand, S. Chatterjea, K. Das, P. Havinga, Wireless Industrial Monitoring and Control Networks: The Journey So Far and the Road Ahead. *Journal of Sensor and Actuator Networks*. 2012; 1(2):123-152.

[24] K. Das, P. Havinga, Evaluation of DECT-ULE for robust communication in dense wireless sensor networks. 3rd International Conference on the Internet of Things, 24-26 Oct 2012, Wuxi, China. pp. 193-190.

[25] P.H de Jong, Power Harvesting Using Piezoelectric Materials. Applications in Helicopter Rotors. PhD thesis. University of Twente. 2013. http://dx.doi.org/10.3990/1.9789036535113