Helicopter Rotor Blade Monitoring using Autonomous Wireless Sensor Network

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Abstract

The advancement on Wireless Sensor Networks for vibration monitoring presents important possibilities for helicopter rotor health and usage monitoring. While main rotor blades account for the main source of lift for helicopters, rotor induced vibration establishes an important source for understanding the rotor performance and blade condition. A discussion on the dual character of blades as rotating structures results in two different interrogation strategies for external and internal dynamic loading on the blade. The first strategy aims for in-flight rotor performance monitoring, while the second pursues health assessment. An overview of different measurements performed on an actual helicopter blade is presented. The measurements include a complete modal analysis using a full wired instrumented blade and a comparison between wireless sensor nodes and wired instrumentation. Additionally, a numerical multibody dynamics model for damage simulation is presented. The experimental and numerical work contribute to the identification of several implications on the migration of condition and health monitoring techniques to a wireless setting.

1. Introduction

Although the main rotor is the principal source for the vibrations in helicopters (Figure 1), rotor monitoring has been done in a rather limited way \textsuperscript{(1)}. This is because existing monitoring technologies are unable to monitor the helicopter blades directly, but rather retrieve the main rotor vibration from the vibrations transmitted to the fuselage. The only exception on blade monitoring is by use of optical tracking using Doppler-based trackers however its scope is rather limited.

The reasons for vibration monitoring on helicopter have evolved throughout time. Initially, improving safety was pointed out as the main objective for vibration levels surveillance\textsuperscript{(3)}. Subsequently reducing maintenance costs while maximizing availability pushed for more assertive vibration data treatment than only establishing safe operating
levels\textsuperscript{(4)}. Later trends on helicopter management pointed towards the integration of safety, usage and maintenance requirements, embodied as Health and Usage Monitoring Systems (HUMS)\textsuperscript{(5)} for which uncertainty reduction on the life prediction becomes relevant.

Figure 1: Main vibration sources in a helicopter\textsuperscript{(2)}

Extension of HUMS to rotor health monitoring has been identified as a key stage for improving damage evaluation and life prognostics of helicopter components. An important stream regarding HUMS development focuses on predictive models for the correlation between blade damage scenarios and their incidence in the fuselage vibration\textsuperscript{(6)}. However this approach faces important challenges for damage identification and classification given the complexity of mechanical systems between the main rotor and fuselage and because of the high structural and aerodynamic-induced damping that reduces signal quality, among other factors\textsuperscript{(1)}.

An alternative path for rotor monitoring is rotating-frame sensing technologies that support data transfer from the rotor system to the non-rotating fuselage equipment\textsuperscript{(7)}. On this frame, the development of autonomous Wireless Sensor Networks (WSNs) becomes relevant for accessing traditionally hard-to-reach locations, such as rotating blades. Furthermore the synchronous capabilities of WSNs favor distributed sensing, which enables advanced interrogation methods for structural integrity and local damage identification\textsuperscript{(8)}.

This paper discusses the development of a vibration monitoring system on helicopter rotor blades using WSNs, which can be addressed from considering the rotating and structural nature of the blades, as presented in section 2. The development of a tailored WSN for helicopter rotor blades is supported by the possibility to perform experiments in an actual helicopter blade as described in section 3. The discussion on the implications of performing advanced interrogation strategies in the WSN context are discussed in section 4. Finally, conclusions are drawn and indications for further work are provided.

2. Interrogation Strategies

Helicopter blades exhibit dual features such as elements from rotors and structures. By understanding the dynamic behavior of composite blades it is possible to extract binding elements for both approaches.
2.1 Blade Dynamics

The main function of the blades is to generate a maximum lift with the least of aerodynamic losses, while enabling the different maneuvers commanded by the pilot. The fulfillment of this function calls for high flexibility throughout the blade span. For instance, helicopter composite blades allow flapping as compensation for dissymmetry of lift during forward flight \(^{(10)}\). Aerodynamic phenomena can affect the blade motion introducing motions at higher harmonics of the rotating speed. Furthermore internal changes on the blade structure can also modify the response of the blade.

2.1.1 Aeroelastic Response

Blade dynamics prescribe three main Degrees Of Freedom (DOF) for the blades, flapping or feathering, lead-lagging and twisting. Two of these DOF, flapping and lead-lagging, are desired -if not enforced- motions of the blades for supporting the compensation of lift dissymmetry and retreating blade stall \(^{(10)}\). However excessive bending leads to excessive fatigue loads for the blades, and furthermore, high vibration levels transferred to the fuselage \(^{(11)}\) and other critical components. Blade twist is used for redistributing the lift over the blade and helps improving the hovering efficiency, but uncontrolled blade torsion can compromise the forward flight performance.

2.1.2 Aerodynamic Excitation

Besides excessive blade motion, aerodynamic instabilities also lead to undesired vibrations. Some of these aerodynamic phenomena are transitory, meaning they occur at discrete segments during the rotation cycle. For instance, in forward flight the rotor may simultaneously encounter transonic flow on the advancing blades, dynamic stall on the retreating blades, and radial flow on the front and back blades. An example of continuous aerodynamic excitation phenomena is Blade-Vortice-Interaction (BVI), which is also the main contributor to helicopter noise \(^{(10)}\).

2.1.3 Structural Behavior

From a structural perspective, main rotor blades are required to be slender, flexible beams, which at the same time must withstand high tensile forces due to centrifugal accelerations and high fatigue loads due to cyclic loading. Given these seemingly opposing requirements between strength and flexibility, anisotropic composite materials offer more freedom to rotor blades designers for tailoring the stiffness properties of structures \(^{(9)}\).

While the blade performance depends on the response of the blade towards external excitations, the blade integrity is governed by the distribution of internal forces acting on the structure. Monitoring of the dynamic quantities of the blade is done by inquiring the structural properties of the blade, to be precise, the mass and stiffness distribution and the structural damping. Structural changes can occur due to external events, such as moisture absorption. In addition, uneven wearing of the protection coating affects the mass distribution of the blade leading to mass unbalance. In a similar fashion, the progression of internal events – failure modes – also can affect the macro properties of the structure, as in the case where the progression of matrix cracking influences the stiffness of the composite material \(^{(12)}\).
2.2 Implications for WSNs

All three aspects mentioned – aeroelastic behavior, aerodynamic excitation and structural behavior – play a simultaneous role for the blade dynamics. A clear segregation of these phenomena can improve the understanding on them and further developments of WSN based monitoring technologies. Therefore it is necessary to establish different interrogation strategies that match each case individually. Table 1 provides a roadmap for the main aspects of two interrogation strategies for the helicopter blade: the *macro* and *meso layers* as discussed in the following paragraphs.

### Table 1: Interrogation strategy for a Helicopter Rotor Blade

<table>
<thead>
<tr>
<th>Interrogation level</th>
<th>Macro</th>
<th>Meso</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td>Rotor performance</td>
<td>Structural integrity</td>
</tr>
<tr>
<td>Blade Dynamics</td>
<td>Aerodynamics/aero-elastics</td>
<td>Structural</td>
</tr>
<tr>
<td>Measurement</td>
<td>Operational Deflection Shape</td>
<td></td>
</tr>
<tr>
<td>Processing</td>
<td>Time waveform</td>
<td>Modal parameters</td>
</tr>
<tr>
<td></td>
<td>Spectral analysis</td>
<td></td>
</tr>
<tr>
<td>Objective</td>
<td>Flight performance</td>
<td>Damage identification</td>
</tr>
</tbody>
</table>

#### 2.2.1 The Macro Layer

The discussion in sections 2.1.1 and 2.1.2 on aeroelasticity and aerodynamics highlights the complexity on the interaction between the these phenomena during helicopter flight. Deployment of autonomous sensors along the blade enables monitoring of key parameters such as root strain, tip displacements and blade torsion, contributing to the blade response understanding.

The effect of flight regime on 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. Correlations of vibration signals from different locations within the same blades – for example the ratio between the root strain and tip displacement – are expected to be less operational dependent than absolute values.

#### 2.2.2 The Meso Layer

The quantification of mass and stiffness distributions is possible by means of modal based methods such as natural frequencies, mode shapes, curvatures, modal strain energy among others\(^{(13-15)}\). An important difference between the structural integrity and the rotor performance strategy lies in the need to reduce the influence of aerodynamics and of the blade level of motion. Exploring the blade structural condition requires more controlled excitations than those occurring during flight conditions, meaning that these have to be executed for ground conditions.
Experimental Modal Analysis (EMA) is the most common method for modal extraction for which the excitation force is known, can be measured or up to certain extent controlled. However this is not always possible for large structures such as helicopter blades. As an alternative, the use of environmental excitations is proposed, as in the case for Operational Modal Analysis (OMA). The drawback of using operational excitations is that the modal parameter extraction becomes more complex than with EMA, which can lead to additional sources of error in the modal extraction (16).

3. Overview of Experimental and Numerical Work

This section presents the test performed by LMS International, the University of Twente and Inertia Technology regarding vibration monitoring for damage detection in helicopter rotor blades in the frame of the project WiBRATE.

3.1 Helicopter Blade – EMA

A composite main rotor blade from a PZL SW-3 Sokol helicopter was used for experimental testing(21). This type of blade is made of Glass Fiber Reinforced Plastic, the structure spar is reinforced with the use of glass roving material and the honeycomb elements are made from nomex. The dimensions of the blade investigated are: length $\approx 7300\text{mm}$, width $\approx 520\text{mm}$, approximate weight 70kg.

A complete EMA with high spatial resolution was carried out to obtain the blade’s modal properties at non-rotating condition, see Figure 2. The blade was suspended with two elastic chords to create a free-free boundary condition. Acceleration was measured in a total of 55 points and a force transducer was used to measure the excitation force exerted by the electromechanical shaker. A burst of random excitation signals was used as an excitation signal.

![Schematic representation of complete modal analysis on Helicopter blade](image)

An additional study was carried out to reduce the number of modes used in the damage detection method. The first six modes were identified as the most relevant, as concluded from a sensitivity analysis for damage detection algorithms. Figure 3 shows the first bending mode, first torsion mode and the sixth mode.

To test the effectiveness of the SHM methods to be evaluated, a second experimental modal analysis was carried out. A small mass weighting approximately 100 grams (0.14% of the total mass) was attached to the blade (the red spot in Figure 2), to cause
system changes and simulate (a reversible) damage. Two modal based techniques were used.

The first one is based on the direct comparison of the vibration modes, and is called Coordinate Modal Assurance Criterion (COMAC)\(^\text{(17)}\). The other SHM technique uses the strain energy formulation\(^\text{(14)}\) and derives it from the mode shape curvatures, which are approximately equal to the second spatial derivative of the displacement mode shapes. Both methods provide normalized damage indices, with which the location of the damage can be determined\(^\text{(18)}\). The experimental results for these methods are presented in Figure 4. Both methods are observed to be successful in identifying the location of the damage (at the blade tip).

![Figure 3: Helicopter main rotor blade vibration modes. First Bending mode (a), first torsion mode (b) and couple mode (c)](image)

![Figure 4: Damage detection methods: (a) COMAC damage index and (b) Modal strain energy damage indicator](image)

### 3.2 Helicopter Blade- Wireless sensor based modal analysis

Figure 5 shows the blade instrumented with wired and wireless accelerometers\(^\text{(19)}\). The classical wired accelerometers were used as a means of comparison of signal and frequency response function (FRF) quality. Support and boundary conditions were similar to the full EMA described previously.
The ProMove 3D developed by Inertia Technology is used as wireless sensor platform\(^{(22)}\). Figure 6 shows the sensor and its technical characteristics. These sensor nodes contain integrated MEMS accelerometers.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Accelerometer, Gyroscope, Compass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless communication</td>
<td>Frequency band 2.4 GHz / IEEE 802.15.4</td>
</tr>
<tr>
<td>Data collection</td>
<td>Sampling rate scales with the number of nodes in the network: 200 Hz for 6 nodes, 100 Hz for 12 nodes</td>
</tr>
<tr>
<td></td>
<td>Synchronization &lt; 10 μs</td>
</tr>
</tbody>
</table>

3.3 Numerical Model: Multibody Blade Model

A 1-D finite element model of the blade was created in a multibody simulation environment\(^{(20)}\), see Figure 7. This method is used to model helicopter blades dynamics at relatively low computational costs in comparison with a complete 3-D Finite Element Model\(^{(23)}\). The multibody model response is compared with the experimental results presented before by simulating the sensor network used. It is therefore used as a virtual test space.

4 Discussion

Vibration monitoring directly at the helicopter rotor blades presents an important advancement in health and usage monitoring systems. Two strategies for rotor blade
interrogation are discussed. The first strategy considers rotor performance during flight conditions, for which aeroelastic and aerodynamic effects are the most relevant. The second strategy relates to structural integrity checks performed at more controlled conditions such as ground rotation.

The autonomous and distributed sensing characteristics of Wireless Sensor Networks are desirable attributes for vibration monitoring of helicopter rotor blades. On the technological implementation side, the most relevant attributes for the WSN design have been targeted by Sanchez et al. as (i) distributed acquisition requirements, (ii) efficient electronics for processing, sensing and harvesting, (iii) communication protocols for high synchronization sensing and (iv) efficient local processing algorithms for reducing data throughput. The experimental work presented has contributed to understand better the aforementioned requirements, apart from the electronics that are not discussed here. Furthermore the role of the numerical model is briefly addressed.

**Acquisition Requirements:** Reducing the acquisition requirements is relevant for reducing the local processing in terms of memory. The frequency bandwidth reduction by limiting the number of nodes necessary for damage identification has an immediate effect on the specifications for the node in terms of memory, processing power, communication bits, etc. However, excessive model simplification can lead to leave developing failures unnoticed reducing the effectiveness of the sensor network. This justifies a (numerical model based) sensitivity analysis. Moreover, an experimental validation comparing the wireless technology with a wired solution is equally important.

**Local Processing** relates to the question to what extent it is efficient to perform operations locally in order to minimize the data (bits) communication. In the experiments, thirty burst cycles were used for the complete modal extraction to ensure good transfer functions. The communication of this time data implies a large power consumption for the node. However, when time averaging of the signal can be done locally, the communication of the averaged data can provide a considerably reduction in energy consumption.

**Synchronization** of wireless aspects becomes critical for performing cross-correlation calculations. Accurate synchronization depends on both the internal clock of the sensor node and on the protocol strategy for synchronization. The relevance of synchronization for a qualitatively good measurement of the frequency response function is shown in Figure 8. In this case, different, non-synchronized data acquisition systems were used. The synchronization correction is performed in the post-processing phase and is observed to yield a significant improvement of the wireless frequency response measurement

Synchronization issues can also become relevant for rotor performance monitoring during flight. It is possible to define periods of measurement, in a similar manner as the burst random excitation for modal analysis, that correspond to the rotation of the blade. This would enable to perform synchronous averaging of the time signal at the node itself.
Numerical Modeling supports the understanding of the effect of several damage scenarios. Several requirements of the WSNs can be evaluated in connection with the possible damage scenarios on the blade. Furthermore, the possibility to simulate non-reversible damages such as delamination and cracks sets a valuable complement to the experimental work. Numerical models also contribute to the definition of several parameters of the WSNs such as sensor layout and expected values of the damage features.

5. Conclusion and Future Work

The experimental and numerical work performed sets the basis for advancing in the embedded character and autonomy of WSNs for helicopter blades by setting requirements for sensing, local processing, energy harvesting and wireless communication. Further testing on the actual blade is directed towards more autonomous sensors, with an increased amount of local processing and power harvesting functionality. Additional methods for damage identification, meeting the requirements of WSNs are under investigation. Finally, more realistic damage conditions such as distributed mass are to be included in the experimental testing.

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References


