HELIICOPTER MAIN ROTOR BLADE MODELING AND EXPERIMENTAL TESTING FOR STRUCTURAL HEALTH MONITORING

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Keywords: structural health monitoring, helicopter blade model, strain energy damage index, vibration based damage detection, bladebeam modeling

ABSTRACT

This work presents numerical and experimental results of a damage detection technique based on strain energy, with the application on a composite helicopter main rotor blade (MRB) from a PZL SW-3 helicopter. The blades from helicopter rotors are a very important structural element - they are very long beam-like structures that undergo different load conditions and aerodynamic forces at different parts of it. The damage detection method used in this study is based on the modal strain energy formulation of a beam. Initially, finite element method (FEM) simulations of a composite MRB blade section were carried out to study the efficiency of the technique proposed and afterwards experimental parameters were extracted via an experimental modal analysis. Vibration modes and natural frequencies were identified by means of a least squares fit (PolyMAX). For this purpose, 55 uniaxial accelerometers were positioned along the blade in a way to measure the most significant vibration modes and an electrodynamic shaker was used to excite the system. Damage was introduced artificially on the blade by attaching a small mass to the MRB, changing its global properties this way. Experimental results for the damage detection technique are shown, and important remarks concerning sensitivity and robustness of the method are also discussed.

1. INTRODUCTION

The blades from helicopter rotors are a very important structural element - they are very long beam-like structures that undergo different load conditions and aerodynamic forces at
different parts of it. These components used to be made mostly of metal parts, plywood or fabric covering with a steel spar [1], but nowadays they are mostly composed of glass fiber reinforced plastics (GFRP) and carbon fiber reinforced plastics (CFRP) laminates, epoxy and honeycomb filled core structures [2].

With the continuous and dominant use of composite material in the aeronautic and rotorcraft industry, the need to accurately model these structures has also increased. It becomes even more important with the emergence of new technologies that rely on an accurate model, such as structural health monitoring [3, 4]. Computational modeling of a composite material system using finite element analysis can become very complex and lead to unreliable results, usually requiring dedicated updating of the model [5]. Moreover, the analysis becomes more complex when there are rotating parts involved - such is the case with the helicopter blades [6]. Obtaining material properties for the system can also become troublesome, especially when defining properties to be used in a finite element model.

Another possibility consists of modeling the flexible blade as a discrete system composed of beam elements [7, 8]. This way, orthotropic properties can be included in the modeling process, with the properties discretely varying with the blade radius. The blade material data necessary for this type of model is simpler and can be obtained by means of static analysis of the blade.

This type of system can also be used to evaluate damage detection techniques [9], as stiffness values can be changed or additional faulty beam elements can be introduced to simulate damage occurring on the blade [10].

1.1 Structural Health Monitoring

The objective of structural health monitoring (SHM) is to continuously monitor a structure during its complete lifetime, being able to detect, locate and even diagnose damage present in multiple locations. Many challenges lie in designing a robust and efficient SHM system - how to detect damage, how to identify it and which types of damage are to be detected - all of these play an important role in determining the sensor network and system architecture to be used.

There are many possible applications for SHM systems, as any structure can be monitored to avoid failure. Of all the applications, the aerospace industry is one of the more motivated ones. Since failures in aircraft can lead to catastrophic incidents, constant monitoring of this sort of structure is very important. Regular maintenance checks can be very expensive, and with the increasing use of composite materials, failures such as debonding, fiber breakage and matrix cracks can be very hard to detect with conventional visual inspection. Nowadays, non-destructive testing is used to detect the sorts of failures previously mentioned. This sort of testing is carried out using ultrasound imaging and x-ray, which can be very expensive as the aircraft is needed to be taken out of operation for the procedure to be carried out. For this reason, SHM techniques aim to provide a better, cheaper and more reliable alternative to the current methods.

This paper focuses on the modeling and experimental testing of a helicopter MRB to be used for SHM applications. The helicopter MRB used in this study belongs to a PZL W-3 Sokol helicopter [11]. The blade is made from glass fiber reinforced plastics, while its D-spar contains glass roving material and is filled with foam. Its trailing edge is filled with Nomex honeycomb elements.

2. MODAL BASED SHM
Modal-based vibration damage detection is a global method that uses modal parameters and properties to track damage and damage progression. The main advantage in modal methods is that local changes in the mass, stiffness and damping matrices are very sensitive in the modal parameters, allowing for good sensitivity in identifying damage, while still not requiring so much frequency bandwidth as wave-based methods.

2.1 The Modal Strain Energy Method

The strain energy method, developed by [12], has been subject to many studies and it has generated further development of the algorithm and damage index indicators. The method takes into account the changes of strain energy in an Euler-Bernoulli beam. The bending strain energy $U_B$ can be obtained by integration of the squared strain over its length $L$:

$$U_B = \frac{1}{2} \int_0^L \left[ EI(\psi''(x))^2 \right] dx$$

where $\psi$ is a vibration mode and $EI$ is the bending stiffness of the beam and can vary along the beam axis. Torsional and axial deformation are not taken into account in this formulation. Their energy expressions [13] can be represented as:

$$U_T = \frac{1}{2} \int_0^L \left[ GJ(\theta_{yz}(x))^2 \right] dx$$

for the torsional energy, and:

$$U_A = \frac{1}{2} \int_0^L \left[ AE(v(x))''^2 \right] dx$$

for the axial strain energy, with $GJ$ and $AE$ being the torsional and axial stiffnesses, respectively, $\theta_{yz}(x)$ the rotation around the x-axis and $v(x)$ the displacement along the x-axis.

Discussions regarding the use of torsional strain energy are presented in [14], where the authors remark that the estimation of the rotation angle $\theta_{yz}$ is a complicated issue and has not been completely solved yet. Moreover, they suggest that incorporating the normal displacement modes $\psi$ in the detection algorithms can provide additional information for the damage detection. The axial modes, in the case of the helicopter blade, will usually occur at much higher frequencies and would require measurements in another axis and consequently will not be considered. Nevertheless, the damage index formulations that will be presented can also be adapted for use with the torsional and axial strain energy, following the formulations on equations (2) and (3).

Based on some assumptions, a damage index can be created using the strain energy formulation described in (1). The damage index used in this work is derived from [15], where an approximation is made based on the assumption that there is only change in the energy quantity at the damaged location and that the overall energy will remain the same. This way, the following damage indicator for a given mode is obtained:

$$\beta_{el,j} = \frac{EI_{el}^0}{EI_{el}^d} \frac{\int_1 \left[ \psi_j''(x)^2 \right] dx}{\int_1 \left[ \psi_j'(x)^2 \right] dx} \cdot \frac{U_{B,j}^0}{U_{B,j}^d} = \frac{NUM_{el,j}}{DEN_{el,j}}$$

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Afterwards, summation is carried out for all considered modes and the damage indicator is normalized:

\[
\beta_{el} = \frac{\sum_{j} NUM_{el,j}}{\sum_{j} DEN_{el,j}} \quad \text{and} \quad Z_{el} = \frac{\beta_{el} - \mu_{\beta}}{\sigma_{\beta}}
\]

(5)

where \( \mu_{\beta} \) is its mean value and \( \sigma_{\beta} \) its standard deviation.

An important remark on this damage indicator is that it is much more sensitive than other damage indicators, since it does not include the integral of the curvature mode shape over the whole beam, smaller values are compared in the fraction. High sensitivity may lead to detection of small damage, but at the same time, it means that the index is more prone to noisy data.

### 3. ROTOR BLADE SIMULATION MODEL

A 1-D finite element model of the blade was created in a multibody simulation environment [16, 17]. This method is commonly used to model helicopter blades [18], as it provides a simple and yet effective way of representing the system’s dynamics, as opposed to a full 3-D finite element analysis.

The blade is discretized into several rigid body sections, each one of them containing inertial and mass properties. Then, each section is interconnected with the next by a flexible beam element that provides the dynamic characteristics of the structure. The beam element is defined by a stiffness matrix, as shown in (6), and it has 6 degrees of freedom at each end - the 3 displacements and 3 rotations, that are directly related to the forces and torques acting on the element. The stiffness matrix element \( EA \) represents the section axial stiffness, \( EI_y \) is the chordwise stiffness, \( EI_z \) the beamwise stiffness, \( GI_x \) the torsional stiffness and \( l \) the length of the discretized section. The inertial properties of the rigid body sections contain the matrix with the main moments of inertia, \( I_{xx}, I_{yy} \) and \( I_{zz} \), as well as the section mass. In total, there are 27 rigid body sections, interconnected by 26 beam elements. Figure 1 shows the blade model used for the simulations.

\[
K = 
\begin{bmatrix}
EA & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{12EI_y}{l^3} & 0 & 0 & 0 & -6EI_z \\
0 & 0 & \frac{12EI_z}{l^3} & 0 & 6EI_y & 0 \\
0 & 0 & 0 & GI_x & 0 & 0 \\
0 & 0 & 6EI_y & 0 & 4EI_y & 0 \\
0 & -6EI_z & 0 & 0 & 4EI_x & 0
\end{bmatrix}
\]

(6)

Figure 1. Multibody beam model of the helicopter main rotor blade

Moreover, to be able to compare the simulation with the experimental results, a sensor network was created for the helicopter blade model. For this purpose, a local coordinate system was created for each sensor location and the sensors were placed in a realistic way when
compared to the experimental modal analysis - the location of the sensors is very important to calculate the modal assurance criterion in a reliable way. Figure 2 shows the model with all the sensors. Section 4.1 shows the details for the experimental modal analysis, the sensor directions, driving point and other important aspects that were also defined on the simulation model.

Figure 2: Main rotor blade model with sensor network - ks are sensors measuring acceleration and fs are sensors measuring force

4. EXPERIMENTAL ANALYSIS AND RESULTS COMPARISON

4.1 Experimental Modal Analysis

An experimental modal analysis was carried out to obtain the blade’s modal properties in a non-rotating condition. The blade was suspended with two elastic chords to create a free-free boundary condition and system excitation was carried out with an electrodynamic shaker.

To suspend the blade, two elastic chords were used to keep it in a steady position for the whole test duration. Even though clamping condition would ideally be more adequate for the blade test, since it better represents the blade’s actual condition when in the helicopter, this sort of boundary condition is very hard to achieve for a test object of its size. To guarantee a free-free boundary condition with the elastic ropes, one should assure that the stiffness of the ropes does not affect the dynamic properties of the system at the desired frequency range.

Accelerometers were chosen as the transducers for the test. Acceleration was measured in a total of 55 points and a force transducer was used to measure the excitation force exerted by the shaker. Figure 3 shows the main rotor blade with the measurement points, driving point and coordinate system. From the 55 accelerometers, 49 measure acceleration in the x direction, to capture beamwise and torsional dynamics, while the other 6 accelerometers measure acceleration in the y direction to capture the lead-lag (in-plane) dynamics. Additionally, a small mass weighting approximately 100 grams was used on a second experiment to create a system change and therefore simulate damage on that location.

The transducers used to measure the acceleration were traditional ICP accelerometers and the input force was measured using a force cell. A schematic representing the test set-up with shaker is shown on Figure 4 and the full list of components used for the tests is shown below, and additional details on the signal acquisition are shown on Table 1.

- LMS SCADAS 3 with 64 measurement channels and 2 output channels
- PC with LMS Test.Lab 11A software
- 55 PCB Accelerometers
- PCB impact hammer
- PCB impedance head
- Electrodynamic shaker with stinger and amplifier
Figure 3: Measurement points on main rotor blade - circled points (10,17,22,29,40,47) represent the acceleration measurements on the y direction, and the point in red represents the excitation point (driving point). The position of the mass used for damage detection is also shown.

Table 1. Data acquisition details

<table>
<thead>
<tr>
<th>Excitation signal</th>
<th>burst random</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of averages</td>
<td>30</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>800 Hz</td>
</tr>
<tr>
<td>Frequency range of interest</td>
<td>8 to 110 Hz</td>
</tr>
<tr>
<td>Frequency resolution</td>
<td>0.1953 Hz</td>
</tr>
<tr>
<td>FRF estimator</td>
<td>H1</td>
</tr>
</tbody>
</table>

4.2 Model and Test Correlation

The helicopter MRB model was created using the structural properties provided by the manufacturer. To replicate the boundary conditions of the experimental modal analysis, 4 springs with low stiffness were attached to the blade model to suspend it. Initially, 8 modes were identified with good correlation between the model and the experimental results. Table 2 shows the modes numbers, natural frequencies of both experimental and computational systems and percentage of difference.

Table 2. Natural frequencies of experimental and simulated systems

<table>
<thead>
<tr>
<th>Mode number</th>
<th>Natural frequency (Hz)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
<td>Simulation</td>
</tr>
<tr>
<td>1</td>
<td>10.32</td>
<td>11.42</td>
</tr>
<tr>
<td>2</td>
<td>20.28</td>
<td>22.45</td>
</tr>
<tr>
<td>3</td>
<td>30.12</td>
<td>34.16</td>
</tr>
<tr>
<td>4</td>
<td>33.75</td>
<td>36.18</td>
</tr>
<tr>
<td>5</td>
<td>49.45</td>
<td>50.80</td>
</tr>
<tr>
<td>6</td>
<td>60.66</td>
<td>64.40</td>
</tr>
<tr>
<td>7</td>
<td>66.88</td>
<td>66.26</td>
</tr>
<tr>
<td>8</td>
<td>86.98</td>
<td>88.56</td>
</tr>
</tbody>
</table>

Additionally, the modal assurance criterion (MAC) was used as a way to correlate computationally and experimentally identified modes. Figure 5 shows the MAC for the 8 modes. Figures 6 through 13 show the experimentally identified modes and their equivalent computational ones.
Figure 4. Schematic of test set-up for the experimental modal analysis

Figure 5. Modal assurance criterion - comparison between simulation and test
4.3 Experimental Structural Health Monitoring Results

To verify the strain energy damage detection method, the computational model and experimental results were used. The objective was to evaluate the effectiveness of the described method by using simulation, as well as test it on the real blade and compare both results. For this purpose, the kinematic sensors in the computational model were used as the actual SHM network and the equivalent sensor network was used on the real blade experiment.

Since the quantities obtained in a classic modal analysis are the displacement modal vectors, there is the need to obtain the curvature mode shapes from the displacement modal vectors. These can be obtained using equation (7):

\[
\kappa = \frac{\psi''}{(1 + \psi'^2)^{\frac{3}{2}}}
\]

where \(\psi'\) and \(\psi''\) are the first and second derivatives of the displacement mode shapes, respectively. For small deformations or displacements, one can approximate \(\psi'^2 = 0\) and thus equation (8) can be used instead:

\[
\kappa \approx \psi''
\]

A known problem related to obtaining the curvature from the displacement mode shapes is the presence of noise [14]. By simply deriving a dataset that is already susceptible to noise will risk amplifying it, which is undesirable in damage detection applications, since these can
lead to false positives. In [19, 20] the central differences approximation is suggested:

$$\kappa = \frac{\psi_{i-1} - 2\psi_i + \psi_{i+1}}{h^2}$$  \hspace{1cm} (9)

This procedure was carried out for both simulation and experimental results, to guarantee the most similarity between cases. Moreover, this requires some additional assumptions are made about the model - to simplify it as a beam-like structure. Since there were more than one line of measurements that could be approximated as a beam, the blade was divided in 3 distinct lines, each one representing an individual beam. Figure 14 shows the added mass location as well as the three beam lines, with the top and bottom ones being used to calculate the energy using the bending formulation, while the middle line uses the in-plane formulation to compute the energy due to the lead-lag vibration modes.

Finally, the strain energy damage index was calculated for the simulation and experimental cases. Initially, a baseline (undamaged) model was considered and then damage was added to the systems. For the simulation case, damage was introduced by reducing the stiffness of one of the beam elements by 20%, while for the real system, a mass was added to a similar location. Another possibility would have been to actually damage the blade, but due to the irreversibility of this action, the added mass was chosen instead. Figure 15 shows the two cases, simulation and experimental damage detection. As it can be seen, the method is efficient in pinpointing the damage location in both simulation and real case scenarios. As expected, there is more noise present in the real system when compared to the simulation.
5. CONCLUSIONS AND REMARKS

The work carried out so far shows the experimental identification, modeling and structural health monitoring of a composite helicopter main rotor blade. The helicopter blade characteristics have been presented and a brief introduction to the needs for structural health monitoring, as well as the modal strain energy method. Additionally, the experimental and simulation models were compared and correlated by means of natural frequency deviation and modal assurance criterion. Finally, the damage detection method was shown for both experimental and simulation cases, putting into evidence the effectiveness of the method.

The modal strain energy method is a very sensitive technique to detect system changes and as such be used in the SHM context. It is important, however, that the appropriate approximations and damage index calculations are used. The more sensitive an index is, the more it will also be prone to detecting false positives in a noisy environment. As such, the robustness/sensitivity of the method has to be chosen specifically for each application.

Future works on this topic include the model update and optimization procedure to obtain a more reliable computational model, as well as the use of different types of sensors, such as strain gauges, for the same purpose.

ACKNOWLEDGMENTS

Fábio Luis Marques dos Santos, first author of this paper, is an Early Stage Researcher at LMS International, under the FP7 Marie Curie ITN project “IMESCON” (FP7-PEOPLE-2010-ITN, Grant Agreement No. 264672). This research was also carried out on the Framework of FP7 ICT Collaborative project “WiBRATE” (FP7-ICT-2011-7, Grant Agreement No. 289041). The authors of this work gratefully acknowledge the European Commission for the support.

REFERENCES

Figure 14: Beam approximations based on measurement points and added mass location (red)

Figure 15: Simulated and experimental damage detection using the strain energy algorithm - application to a helicopter main rotor blade


