Off-axis loading in rotor blade fatigue tests with elliptical biaxial resonant excitation

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Abstract. In their lifetime of 20-25 years, wind turbine rotor blades are subjected to high-cycle fatigue. Hence, new rotor blade designs need to undergo cyclic fatigue tests to show that they fulfill the reliability requirements. For these tests, a blade prototype is loaded consecutively in its flapwise and lead-lag directions, which does not represent the actual loading in the field very well. This applies especially for the off-axis load directions of the blade, i.e., the load directions between flapwise and lead-lag directions. By combining the two consecutive tests into one biaxial test, these loads can be improved. Exciting both directions at the same time also generates loads in the off-axis directions.

This work investigates the loading of a biaxial fatigue test using elliptical biaxial resonant excitation. By changing the phase angle of the elliptical excitation, the loading of the blade can be altered to better represent the operational conditions of the blade.

1. Introduction

Rotor blades for wind turbines are subjected to high-cycle fatigue during their lifetime of 20-25 years. To show that a new blade design fulfills the reliability requirements, it is subjected to a cyclic test campaign as part of the certification process. These fatigue tests are mostly executed according to the current IEC 61400-23 [1] and DNV GL AS 0376 [2] standards. Usually, the fatigue testing consists of two consecutive tests, i.e., in the flapwise and lead-lag directions. Each fatigue test normally involves exciting the blade at or near its corresponding natural frequency, thereby inducing bending moments along the blade in the corresponding direction which need to match or exceed the required target loads of the test. This combination of two unidirectional tests does not necessarily represent the full loading envelope in the field, as analyses of the rotor blade field conditions by Rosemeier et al. [3] have shown. Combining these two uniaxial tests into one biaxial test by exciting the blade in both directions simultaneously is one approach to reduce testing time and to induce a more realistic loading. Biaxial testing has been a focus of research for years [4–11], ranging from random phase resonant tests to phase locked tests using resonant or forced excitation.

This work investigates a test with phase locked biaxial excitation using the same frequency for both directions, which results in an elliptical deflection path of the blade cross-sections. To perform such a test in resonance, the natural frequencies for both directions need to be equalized as proposed by Post et al. [12]. Such a frequency adjustment can be realized with the help of virtual masses [12] or stiffness elements [13], which only affect one of the two blade directions.
These virtual masses and stiffness elements are attached at specific positions along the blade’s length. They serve to modify the natural frequencies as stated above, but are also used to adjust the bending moment distributions to target moment distributions. Such a test setup is depicted in figure 5.

This type of elliptical biaxial fatigue test not only introduces loading in the main directions of the rotor blade, but also in the off-axis directions, i.e., the load directions between flapwise and lead-lag directions. This work investigates these off-axial loads and introduces a method which uses the excitation phase difference to adapt the off-axial loads of a given test setup, while keeping the loads in the main directions almost constant. Furthermore, an optimization method to design a test setup directly suited to these off-axial loads is proposed, based on the results from an earlier work [13].

2. Load requirements
A major requirement of any rotor blade fatigue test is the target moment distribution. This is the bending moment range which needs to be achieved or exceeded within a specific area of interest (AoI) along the blade to achieve the required fatigue damage. These values are based on load and damage calculations and are usually given only for the flapwise and lead-lag directions. Since biaxial fatigue tests also introduce off-axis loading, further targets need to be defined. Figure 1 shows schematically the normalized target ranges for the main and off-axis directions at an arbitrary cross-section along the blade. Combining the target loads for all directions results in the target envelope displayed. This represents a typical case provided by the industry. The objective of this work is to be able to satisfy not only the flapwise and lead-lag target moments but also the off-axis targets.

![Figure 1. Target bending moment ranges for the main and off-axis directions at arbitrary cross section along the blade.](image)

3. Approach
For the initial investigation of off-axis loads in an elliptical biaxial fatigue test, the test setup design from Melcher et al. [13] is used. This setup was derived from an optimization without considering the off-axis loads. This was based on a finite element harmonic simulation of the test, which uses beam elements to represent the blade. For the simulation, they proposed a
fixed phase angle of 90° between the flapwise and lead-lag motion of the blade at the position of excitation. The excitations are scaled in order to match or exceed the flapwise and lead-lag target moments within the AoI along the blade.

In this work, the same harmonic simulation is used, but the post-processing of the simulation is extended to also evaluate the load envelope and the off-axis bending moments along the blade.

The approach used in this work is to modify the phase angle to improve the off-axis loading. Changing the phase angle changes the load envelope and the off-axis loads considerably, while the loading in the main directions remains similar to before due to the linear scaling scheme of the harmonic simulation. The phase angle can thus be adjusted to find the load envelope which most closely matches the off-axis target loads, as demonstrated below.

4. Parametric study
First, the off-axis loads and load envelopes of the biaxial test setup are evaluated while the phase angle is kept at the given 90°. This gives the ratios between test and target moments for various directions as shown in figure 2(a). Within the AoI, a maximum load ratio of 1.48 in the 60° load direction and a minimum of 0.64 in the 120° load direction are found. This reveals that the loads in the off-axis directions are poorly matched. Also, the comparison of test and target load envelopes shows a poor correlation in general, by way of example the cross-section at 35% blade length in figure 2(b).

![Figure 2. Test-to-target load ratio in different load directions along blade (a) and load envelopes at 35% blade length (b) for an excitation phase angle of 90°.](image)

Changing the excitation phase angle while keeping the rest of the test setup the same significantly changes the load ratios in the off-axis directions.

Simulations are thus performed for all possible phase angles from -180° to 180° in 5° steps. Selecting the maximum and minimum load ratio within the AoI for each load direction from these simulations results in the plots shown in figure 3. Since the simulation scheme always scales the excitation as described above, the minimum load ratio of the flapwise and lead-lag directions always equals one, as seen in figure 3(b).

The phase angle of 90°, which was used previously, is highlighted with a dotted line. From the data shown in figure 3, it is apparent that a phase angle of 50° (highlighted by a dashed line) results in the best possible load envelope for the given test setup. Using a phase angle of 50° improves the off-axis load distribution along the blade considerably, as shown in figure 4. The maximum load ratio dropped to 1.12 in the 30° direction and the minimum load ratio increased to 0.94 in the 60° direction.
Figure 3. Maximum (a) and minimum (b) Test-to-target load ratio within AoI over phase angle for different load directions.

Figure 4. Test-to-target load ratio in different load directions along blade (a) and load envelopes at 35% (b) blade length for an excitation phase angle of 50°.

At the same time, the loads in the main directions stay almost the same compared to the large changes in the off-axial loads. Nevertheless, the maximum overload in the flapwise direction still increases from 5% at 90° to 10% at 50°. When only the main directions are considered, these being the most important ones for the fatigue tests of rotor blades, the load distribution becomes significantly worse. To avoid this effect, the off-axial loads and the phase angle need to be considered in the design process of the test setup itself. To this end, an optimization of the
test setup using the phase angle as an additional design parameter is performed as described below.

5. Optimization
5.1. Objective and constraints
To find a new test setup using elliptical biaxial resonant excitation, an optimization is performed based on previous results [13], the objective being to reduce the total testing time. Therefore, a single objective optimization was used to maximize the test frequency, while constraints were applied to the maximum load ratios in the main directions.

In this work, the focus lies on the load envelopes and the consideration of the phase angle. Hence, the load ratios need to be considered as the objective of the optimization. Instead of just using the maximum and minimum loads within the AoI, a quality measure computation is introduced to evaluate the load distribution of a single load direction using equation 1, which is based on the established method of least squares:

\[
Q_i = \int_{r_S}^{r_E} \left( \frac{M_{i,\text{test}}(r)}{M_{i,\text{target}}(r)} - 1 \right)^2 dr
\]  

Here \( Q_i \) is the quality level of any load direction \( i \), and \( M_{i,\text{test}}(r) \) and \( M_{i,\text{target}}(r) \) are the test and target bending moment distributions along the blade length \( r \). The radii \( r_S \) and \( r_E \) are the positions along the blade where the AoI starts and ends. To combine the quality measures of all load directions into a single quality measure \( Q_{\text{total}} \), while placing emphasis on the blade’s main directions, they are summed up in the weighted equation 2:

\[
Q_{\text{total}} = \frac{3 \cdot Q_{\text{flapwise}} + 3 \cdot Q_{\text{lead-lag}} + Q_{30^\circ} + Q_{60^\circ} + Q_{120^\circ} + Q_{150^\circ}}{10}
\]  

Using this combined value, the load distribution of a specific test setup can be evaluated. By using this measure together with the testing time as the objectives, an optimization is performed as follows:

Minimize: Quality level \( Q_{\text{total}} \) and testing time \( T = \frac{\text{cycle number } n}{\text{excitation frequency } f_{\text{exc}}} \)

With respect to: flapwise and lead-lag mass or stiffness at each position and phase angle

Subject to:
- \( 1.00 \leq \frac{M_{\text{flapwise,\text{test}}}}{M_{\text{flapwise,\text{target}}}} \leq 1.07 \) within AoI,
- \( 1.00 \leq \frac{M_{\text{lead-lag,\text{test}}}}{M_{\text{lead-lag,\text{target}}}} \leq 1.07 \) within AoI,
- \( 0.80 \leq \frac{M_{i,\text{\text{test}}}}{M_{i,\text{target}}} \leq 1.20 \) within AoI for all off-axis loads,
- \( 0.95 \leq \frac{f_{\text{eig,\text{flapwise}}}}{f_{\text{eig,\text{lead-lag}}}} \leq 1.05 \),
- \( F_A \leq 70 \text{ kN} \) for all element forces

While the load distributions are considered in the objective, they are also used in the constraints to avoid single peaks of load deviation. Since the main directions are still the most important ones, no underloading and a maximum overload of 7% is allowed. For the off-axis directions, a maximum deviation of ±20% from the target load is allowed.

The design space available for the optimization is listed in table 1.

At each position along the blade and for each direction, only one spring element or one virtual mass can be applied, but not both at the same time. The position of the excitation
Table 1. Boundary conditions for load elements and phase angle.

| Position along blade length | 26%  | 38%  | 48%  | 62%  | 76%  | 88%  |
|-----------------------------|------|------|------|------|------|------|
| Maximum flapwise spring stiffness [kNm$^{-1}$] | 120  | 80   | 60   | 40   | -    | -    |
| Maximum flapwise virtual mass [t] | 19.5 | 6.5  | 4.1  | 2.5  | -    | -    |
| Maximum lead-lag virtual mass [t] | 19.5 | 10.5 | 6.3  | 4.1  | -    | -    |
| Maximum for loadframe mass [t] | 19.5 | 6.5  | 4.1  | 2.5  | 1.0  | 0.6  |
| Phase angle | min: $35^\circ$; max: $70^\circ$ |

elements is fixed at 48% blade length, which previous investigations have shown to be the best of the available positions. For more details on the simulation and parameter procedures, see Melcher et al. [13]. For the optimization, the multi-objective particle swarm algorithm OMOPSO developed by Sierra et al. [14] is used.

5.2. Optimization results
The final setup which was chosen from the optimization results is shown in figure 5. The phase angle of this setup is $50.7^\circ$.

![Figure 5. Optimized fatigue test setup with flapwise (a) and lead-lag (b) elements.](image)

Figure 5. Test-to-target load ratio in different load directions along blade (a) and load envelopes at 35% (b) blade length of new optimized test setup.
The resulting test-to-target load ratios are shown in figure 6. The maximum load ratio is 1.08 at 30° load direction at the end of the AoI, while the minimum load ratio is 0.96 at 120° load direction at the start of the AoI. The maximum flapwise and lead-lag overloads are each reduced to 7%. The testing time, on the other hand, is only increased by 0.6% compared to the test setup of Melcher et al. [13].

Taking the phase angle into consideration and including the test-to-target load ratios as objective functions leads to smaller load deviations than changing the phase angle of a predefined setup. This becomes apparent when comparing figure 4 to figure 6.

6. Conclusions
Elliptical biaxial fatigue tests of rotor blades induce loads in more than the traditional flapwise and lead-lag directions. This work demonstrates how test-to-target load ratios in these off-axis directions are adequately achieved by modifying the excitation phase angle. The optimization-based design tool presented considers the phase angle in an early design stage of the fatigue test setup. Unlike a conventional top-to-bottom approach, where the phase angle is varied for a predefined test setup, this optimization approach can consider interdependencies between phase angle, off-axis targets and load elements. A comparison shows that such a parametric study and the optimization-based approach arrive at the same phase angle, whereas the corresponding test setups exhibit differences in the position and size of the positioned mass and stiffness elements. Overall, taking the phase angle into consideration in the early test setup design process facilitates the time-efficient and precise definition of the load envelopes. Future work will include the validation of these numerical results in a real test.

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