Technical Disclosure[1]

1. Title

A Method of Fatigue Testing Wind Turbine Rotor Blades in Off-axis Direction using Single-Axis Excitation

2. Publication date

13th Aug 2026

3. Publication venue

https://www.gevernova.com/wind-power/about/technical-disclosures

4. Publication type

Technical Disclosure

5. Abstract

A method and test system are disclosed for fatigue testing a wind turbine rotor blade in a selected off-axis, non-orthogonal loading direction using only a single-axis active load-introducing device. The system includes a single-axis exciter operated at or near a natural frequency of the test setup and one or more pendulum devices arranged to modify the blade system mode shape so that the resulting blade motion aligns with a target off-axis loading direction. The exciter forcing direction is aligned with the target loading direction within approximately +/-10 degrees relative to the blade coordinate system, for example by pitching the blade, tilting the exciter, or both. The pendulum devices are configured to apply inertia force primarily in one direction and minimally in other directions so that the blade mode shape is tuned toward the desired loading direction. The disclosed approach enables off-axis fatigue testing of blade regions and design features that are not adequately assessed by conventional orthogonal flapwise and edgewise fatigue testing, while reducing hardware complexity relative to multi-exciter systems.

6. Technical field

The present disclosure relates to fatigue testing of wind turbine rotor blades. More particularly, the disclosure relates to systems and methods for applying controlled non-orthogonal or off-axis fatigue loading to a wind turbine blade using a single-axis excitation system in combination with pendulum-based mode-shape modification.

7. Background

Conventional blade fatigue testing is typically performed in orthogonal directions such as flapwise and edgewise loading. While such testing is useful for validating certain primary structural regions, it may not adequately reproduce loading states experienced by blade features located in non-orthogonal regions of the blade. As a result, some critical design features, including sandwich panel regions, flatback glue joints, and other laminate structures subjected to non-orthogonal fatigue effects, may not be fully validated.

Existing approaches for generating off-axis loading on a wind turbine blade commonly rely on two or more load-introducing devices or exciters. Such arrangements can increase system complexity, energy requirements, setup effort, and cost. Further, prior approaches that pitch the blade may use pitch primarily to adjust the mean load direction associated with gravity effects, rather than to produce blade motion aligned with a desired off-axis test direction.

Accordingly, there is a need for a simpler and more efficient fatigue testing approach that can produce off-axis blade loading and validate non-orthogonal blade regions without requiring multiple active exciters.

8. Summary of the disclosure

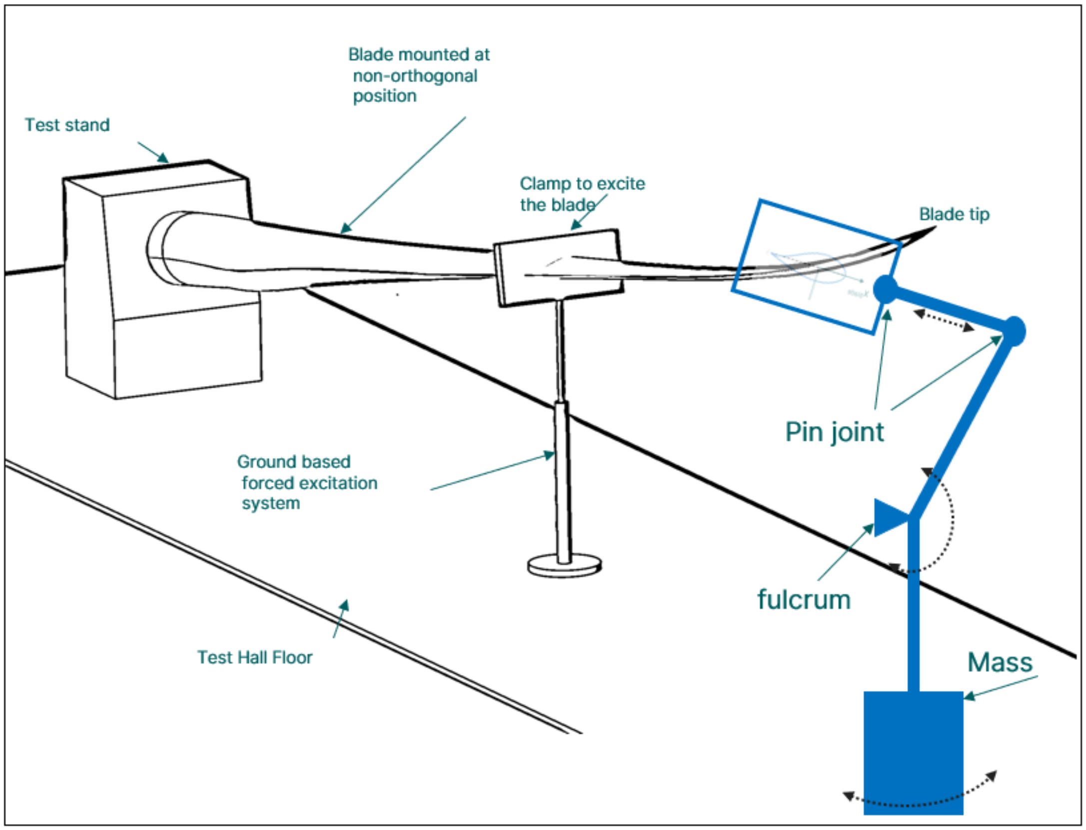
The disclosure provides a fatigue testing device and method for testing a wind turbine blade in a specific off-axis direction using only one single-axis active load-introducing device and one or more pendulum devices. The exciter is operated at or near a natural frequency or resonance condition of the test setup system. The forcing direction of the exciter is aligned with a target loading direction, preferably within approximately +/-10 degrees relative to the blade coordinate system.

Alignment between the exciter direction and the target loading direction may be achieved by pitching the blade, tilting the exciter equipment, or a combination thereof. Because the natural blade mode shape may not inherently align with the desired loading direction, one or more pendulum devices are added to the system to modify the mode shape. These pendulum devices apply inertia force predominantly in one direction and substantially less in other directions, thereby shifting the system response so that the blade motion aligns with the desired off-axis loading direction.

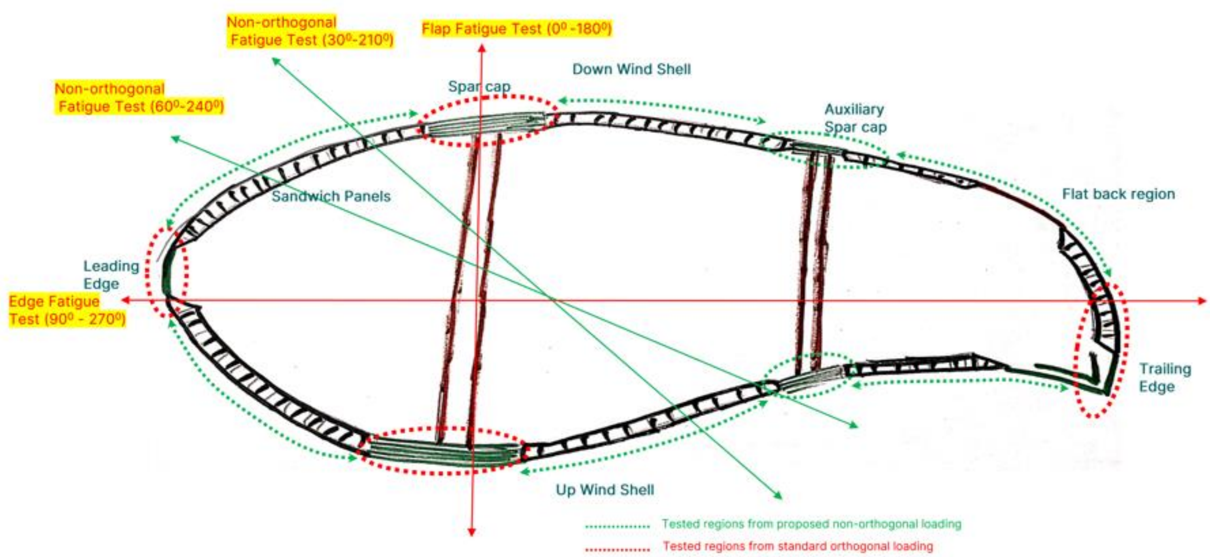
In this manner, the system enables testing in selected off-axis directions using a single active exciter rather than multiple exciters. The disclosure further contemplates modified pendulum configurations capable of imparting inertia force across a range of off-axis directions, for example from about 0 degrees to about 90 degrees from horizontal.

9. Brief description of drawings

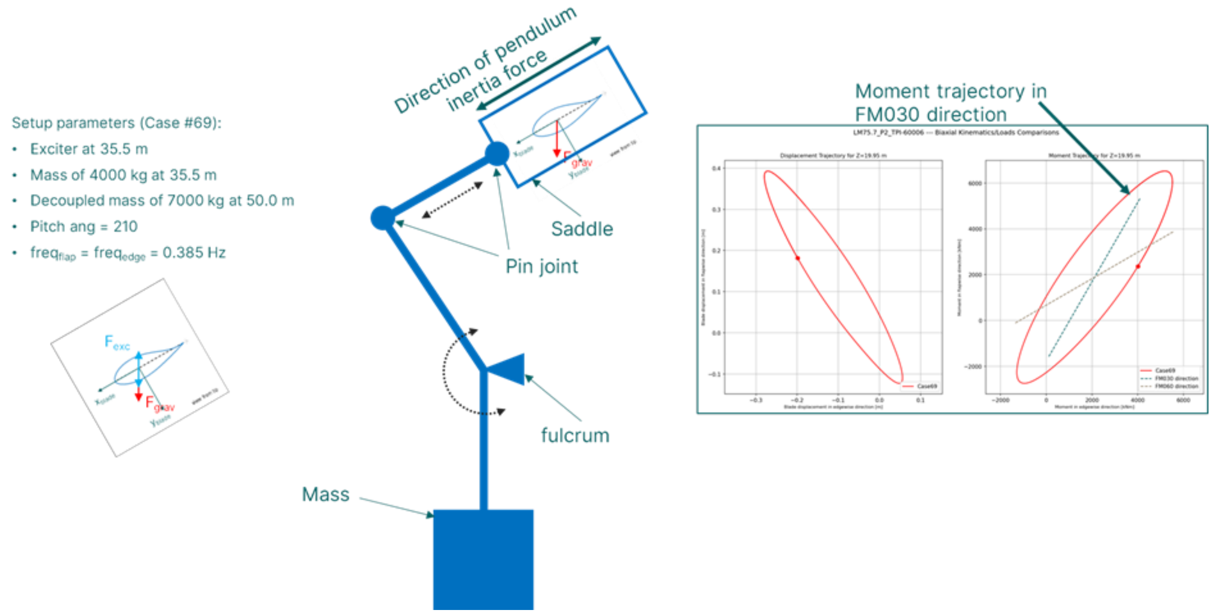
[FIG. 1] illustrates a conventional single-axis fatigue testing arrangement in which a blade is oriented in a standard flap direction.



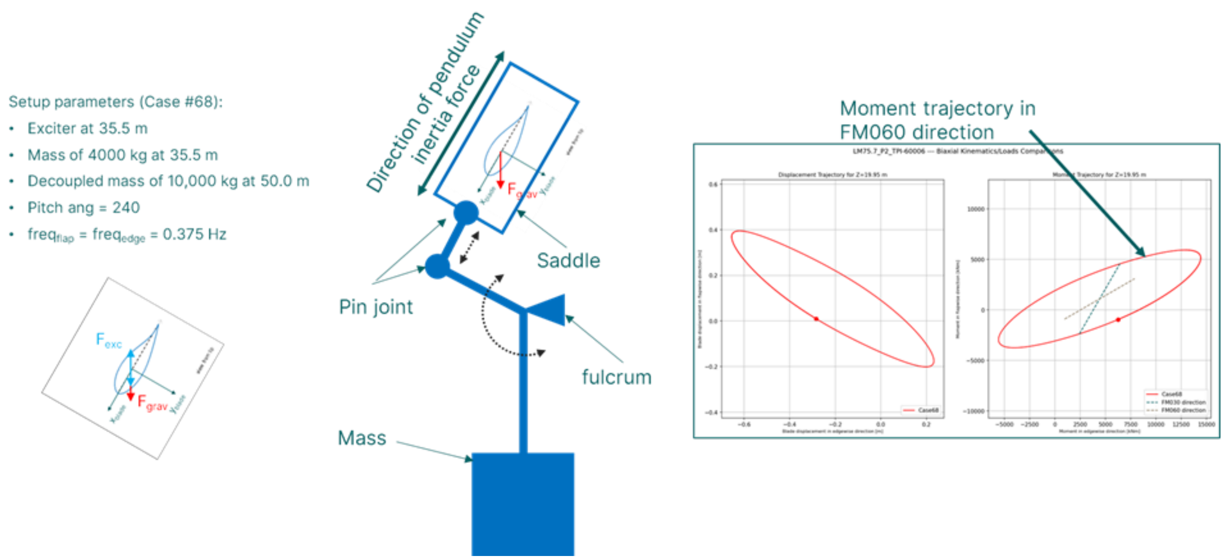
[FIG. 2] illustrates a single-axis exciter and pendulum system with the blade pitched at a non-orthogonal angle to achieve off-axis loading.



[FIG. 3] illustrates typical testing regions that can be assessed using single-axis forced excitation while the blade is oriented in a non-orthogonal direction, compared with standard fatigue testing in orthogonal directions.



[FIG. 4] illustrates a first simulated setup in which the mode shape is adjusted to induce blade movement and moment trajectory in an FM030 direction.



[FIG. 5] illustrates a second simulated setup in which the mode shape is adjusted to induce blade movement and moment trajectory in an FM060 direction.

10. Detail description

A wind turbine blade is mounted in a fatigue test setup, such as at a test stand or hub-side fixture, and a single-axis active exciter is coupled to the blade to introduce periodic loading. The exciter may be ground-based or otherwise supported relative to the test installation. The blade is positioned so that the forcing direction of the exciter is aligned with a desired off-axis loading direction within a specified angular tolerance, such as approximately +/-10 degrees. This alignment may be accomplished by pitching the blade to a selected angular orientation, by tilting the exciter, or by adjusting both.

Because the blade's inherent modal response may not coincide with the desired off-axis direction, one or more pendulum devices are coupled to the blade system. Each pendulum device may include a mass supported about a pin joint or fulcrum and arranged so that its inertia force acts primarily in a selected direction. By appropriately selecting pendulum geometry, mass, position, and orientation, the pendulum modifies the dynamic mode shape of the blade system. This causes the resonant motion of the blade to align more closely with the desired off-axis testing direction.

The system is preferably excited at or near a natural frequency of the configured setup. Under these conditions, the blade response is amplified efficiently, enabling the desired fatigue loading direction to be achieved with a single active exciter. The pendulum device may be configured as a decoupled mass arrangement positioned along the blade span. In representative simulated examples, the exciter is located at approximately 35.5 m, with an added mass of about 4000 kg at the same location and a decoupled mass placed at about 50.0 m. In one example directed to FM030 loading, the decoupled mass is about 7000 kg, the blade pitch angle is about 21.0 degrees, and the flapwise and edgewise frequencies are each about 0.385 Hz. In another example directed to FM060 loading, the decoupled mass is about 10,000 kg, the blade pitch angle is about 24.0 degrees, and the flapwise and edgewise frequencies are each about 0.375 Hz.

In operation, the exciter force, gravity effects, pendulum inertia force, and blade dynamic characteristics interact so that the blade moves in a direction that produces a moment trajectory corresponding to the desired off-axis direction. The disclosed approach therefore allows the fatigue test to load blade regions associated with non-orthogonal structural features, rather than being limited to conventional spar-cap or leading/trailing-edge dominant validation.

Simulation and automation may be used to determine suitable setup parameters. Above examples describe successful simulation in a blade fatigue test simulator, in which the proposed testing design method and interpretation of test outcome demonstrated that the blade can be controlled to move in the desired off-axis direction. These simulations showed promising results for induced motion in both FM030 and FM060 directions.

11. Advantages

The disclosed method provides several technical and commercial advantages.

First, the testing device is simpler than other systems used to achieve similar off-axis blade loading because it can use one single-axis exciter rather than two or more load-introducing devices.

Second, the method expands fatigue validation beyond standard orthogonal flapwise and edgewise test regions. This enables evaluation of critical blade features located in non-orthogonal regions, including sandwich panels, flatback glue joints, and other laminate regions susceptible to fatigue-related damage.

Third, the method may help detect structural vulnerabilities earlier in the development cycle, including vulnerabilities associated with field-observed laminate fatigue and cracking.

Fourth, the method supports more comprehensive blade validation strategies for commercial blade products and future blade designs.

Fifth, the method can help reduce quality issues in the field, avoid retrofit repair costs, reduce turbine downtime, and mitigate customer dissatisfaction and reputational impact.

12. Example Embodiments

In one embodiment, a fatigue testing system for a wind turbine blade includes a single-axis exciter actuating at or near a natural frequency of the test setup and at least one pendulum device configured to modify the blade mode shape so that blade motion aligns with a target off-axis loading direction.

In another embodiment, the single-axis exciter is oriented so that its forcing direction is within approximately +/-10 degrees of the target loading direction relative to the blade coordinate system.

In a further embodiment, alignment is obtained by pitching the blade, tilting the exciter equipment, or both.

In another embodiment, the pendulum device is configured to impart inertia force primarily in one direction and minimally in other directions, thereby selectively influencing one or more blade mode shapes.

In one specific example embodiment, a setup for inducing FM030 loading includes an exciter at about 35.5 m, a 4000 kg mass at about 35.5 m, a decoupled mass of about 7000 kg at about 50.0 m, a blade pitch angle of about 21.0 degrees, and operating frequencies of about 0.385 Hz.

In another specific example embodiment, a setup for inducing FM060 loading includes an exciter at about 35.5 m, a 4000 kg mass at about 35.5 m, a decoupled mass of about 10,000 kg at about 50.0 m, a blade pitch angle of about 24.0 degrees, and operating frequencies of about 0.375 Hz.

In another embodiment, a modified pendulum is capable of imparting inertia force in off-axis directions ranging from about 0 degrees to about 90 degrees from horizontal.

13. Industrial Applicability

The disclosed systems and methods are applicable to wind turbine blade development, certification support, prototype validation, production design verification, test-center operations, and fleet reliability improvement programs. The method is particularly useful for testing large utility-scale rotor blades in cases where non-orthogonal loading conditions are relevant to blade durability. The approach may be implemented in blade test halls, research centers, OEM validation facilities, and independent wind blade testing laboratories.

14. Variations and Alternatives

Various modifications may be made without departing from the scope of the disclosure. For example, the number, size, location, and configuration of the pendulum devices may vary depending on blade size, target mode shape, and desired off-axis loading direction. The pendulum may use different linkage, pivot, arm, saddle, or mass arrangements. The exciter may be mounted or supported in different ways and may be tilted instead of, or in addition to, pitching the blade.

The target off-axis direction may be selected from a range of angles according to the blade region or structural feature to be validated. Different resonant modes, mass distributions, and control strategies may be used to tune the system response. Simulation tools, control algorithms, and automated setup optimization routines may be employed to determine appropriate exciter location, pendulum parameters, pitch angle, and frequency conditions.

The method may also be adapted for different blade lengths, blade constructions, test stand architectures, and test objectives. In some implementations, additional passive elements or decoupled masses may be used while still maintaining a single active excitation axis.

15. Conclusion

This disclosure describes a practical and simplified method for fatigue testing wind turbine rotor blades in off-axis directions using a single-axis excitation system combined with one or more pendulum devices for mode-shape modification. By aligning the exciter with a target off-axis direction and tuning the blade system response through pendulum-induced inertia effects, the disclosed approach enables testing of non-orthogonal blade regions that are not adequately addressed by conventional orthogonal fatigue testing. The method reduces complexity relative to multi-exciter systems while improving blade validation capability, thereby supporting more robust blade design and reduced lifecycle risk.

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