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Evaluation of the New B-REX Fatigue Testing System for Multi-Megawatt Wind Turbine Blades

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Evaluation of the B-REX Fatigue Testing System for Multi-megawatt Wind Turbine Blades[*†]

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The National Renewable Energy Laboratory (NREL) recently developed a new hybrid fatigue testing system called the Blade Resonance Excitation (B-REX) test system.[1,2] The new system uses 65% less energy to test large wind turbine blades in half the time of NREL's dual-axis forced-displacement test method with lower equipment and operating costs. The B-REX is a dual-axis test system that combines resonance excitation with forced hydraulic loading to reduce the total test time required while representing the operating strains on the critical inboard blade stations more accurately than a single-axis test system.

The analysis and testing required to fully implement the B-REX was significant. To control unanticipated blade motion and vibrations caused by dynamic coupling between the flap, lead-lag, and torsional directions, we needed to incorporate additional test hardware and control software.

We evaluated the B-REX test system under stable operating conditions using a combination of various sensors. We then compared our results with results from the same blade, tested previously using NREL's dual-axis forced-displacement test method. Experimental results indicate that strain levels produced by the B-REX system accurately replicated the forced-displacement method. This paper describes the challenges we encountered while developing the new blade fatigue test system and the experimental results that validate its accuracy.

I. Introduction

We conduct wind turbine blade fatigue tests to verify a blade's ability to sustain the operating loads it is exposed to during its design life of 20-years or more. During that lifespan, blades can experience as many as 10^9 load cycles. To determine the testing loads, the operating load cases are rainflow counted and used to calculate design equivalent flap (out-of-plane) and lead-lag (in-plane) design equivalent loads (DELs). Because it would take approximately 30 to 60 years to apply 10^9 load cycles to a blade with the cycle speeds used in blade testing, the test loads are typically amplified to reduce the number of cycles required [3,4,5] to complete the tests in just a few months. Further amplification of the test loads can elevate them to an extreme load level that might induce a different mode of failure, thus invalidating the test. Although testing laboratories do not all agree on the exact degree of load amplification, they do agree that increasing the cycle speed is a valid way of reducing test duration. However, as blade size has grown over the years, the test time has increased because the hydraulic system requirements for forced loading increase at a cubic rate with blade length[2]. Although the B-REX system provides an alternative test method that overcomes this limitation, it's development presented a number of challenges.

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[†] This invention is protected by the Patent Cooperation Treaty under PCT/US02/20991, filed in July 2002.

II. Description of Testing Methods

Forced-displacement dual-axis fatigue tests (shown in Figure 1) are conducted at cycle frequencies well below the fundamental flap natural frequency of wind turbine blades. As blades increase in size, test speeds decrease, and the time to complete a test becomes unacceptably long. Larger blades also require very large displacements and, as such, special hydraulic equipment for each test. Increasing actuator sizes requires increasing expenditures in energy and equipment cost.

Figure 1. NREL's dual-axis force-displacement fatigue test

The forced-displacement fatigue tests commonly performed on wind turbine blades have the following characteristics [6,7].

A. Forced-Displacement Fatigue Test Properties

- Excitation frequency is much lower than natural frequency (a quasi-static system)
- Actuator force and blade displacement are in-phase
- Actuator force and displacement directly correlate with bending moments
- Actuator displacement is dictated by blade deflections (longer actuators for larger blades)
- Inertia loads are small compared to applied loads

To mitigate some of the issues presented with forced-displacement blade fatigue testing, NREL created the B-REX test system, which reduces the time and cost associated with performing fatigue tests. As shown in Figure 2, the B-REX test system replaces the large flap load hydraulic actuator with a resonance induction system mounted on the blade to induce motion in the flap direction. A floor-mounted actuator attached to a bell crank provides forced hydraulic motion in the lead-lag direction.

Figure 2. NREL's B-REX test system.

This bell-crank system consists of a long pushrod connected to the blade and a pivoting bell crank that converts the vertical actuator forces to horizontal pushrod forces.

The B-REX test system can be described by the following characteristics.

B. B-REX Fatigue Test System Properties

- Excitation frequency is at or near resonance frequency with high inertia loads (dynamic system).
- Actuator force and blade displacement are 90 ° out-of-phase in flap direction.
- Actuator force is proportional to but a fraction of the required quasi-static force.
- Flap actuator stroke is not directly dependent on blade displacements.
- Inertia loads are significant compared to the applied load.

Note that conventional single-axis blade fatigue resonance systems, which use eccentric mass exciters are commonly used in to test blades. To regulate blade displacement they adjust the excitation frequency [8,9]. The B-REX test system maintains the same excitation frequency throughout the fatigue test. With the B-REX system, the linear displacement of the excitation mass is used to control the blade displacement. This distinction is very important when two-test axes are used because a constant excitation frequency is necessary to maintain proper phase angle control between the flap and lead-lag displacements.

In the first step toward creating the B-REX test system, we implemented only the single-axis flap excitation using linear hydraulic actuators. This step was very straightforward and we found no significant issues other than the anticipated restraints needed to secure the hydraulic lines.

The most significant problems related to the implementation of the B-REX system arose when the lead-lag axis of loading was introduced in conjunction with the flap motion. Significant coupling between the two axes added unanticipated complexity. This paper describes how we mitigated these problems.

III. Dynamic Blade Test Model

To develop the B-REX test system, we created a dynamic model of the system with the following assumptions.[2]

- The blade approximates a slender rod (axial loads are negligible).
- Blade deflections are within the linear elastic range of blade deflections.
- Blade motion can be accurately described using time invariant EI values.
- Torsional blade stiffness is very large and torsional motion is insignificant.
- A decoupled four-degree of freedom (per element) beam finite element model (FEM) is sufficient to model blade motion.

- Lead-lag motion is kinematically constrained by the bell crank mechanism
- Forces applied purely along a predefined axis do not contribute to orthogonal blade loading.

Based on these assumptions, we created a dynamic model of the blade test system using Simulink to simulate fatigue test behavior (Figure 3).

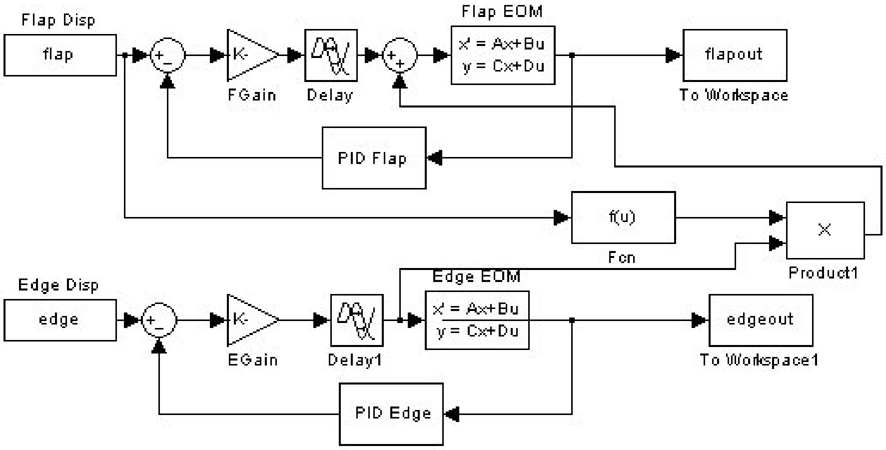

Figure 3. Original Dynamic blade fatigue test system model.

An important aspect of the fatigue test system that was deficient in this original model was the nonlinear flap force introduced by the pushrod used to introduce lead-lag forces into the system. The pushrod introduces forces in both the flap and lead-lag directions whenever the pushrod is acting non-orthogonal to the blade flap motion. As the blade moves in the flap direction, the pushrod angle moves through a range of small angles that induce small but significant flap forces. The flap forces introduced by the pushrod are undesirable and potentially detrimental to the operation of the resonance test system because they can exceed the magnitude of the resonance exciter forces, which are relatively small compared to forced actuator loads. Therefore, we need to model the pushrod as a two-force member to include this influence and achieve the required system accuracy.

Figure 4 shows a photo of the initial blade test configuration for the resonance test system. Note the angle of the pushrod with respect to the blade.

Figure 4. Original bell-crank configuration.

Although the geometric differences are subtle, this configuration was not acceptable for performing a fatigue test because the flap forces introduced by the pushrod overwhelmed the forces introduced from the resonance test apparatus. Experience from dual-axis forced-displacement testing suggested that orientating the pushrod horizontally would minimize coupling between the flap and lead-lag displacements. Unfortunately, the fundamental flap mode shape for the initial blade had a displacement path that was not exactly in the flap direction (vertical test axis) and the path of the blade at the location of the lead-lag actuation force was 12° from the vertical axis for the initial test sample. Because the mean pushrod position was not orthogonal to the blade's motion, the pushrod forces were sufficient to create significant flap motion in the blade even without the resonance induction system being energized. In this case, the resulting flap blade response was greater than the target displacements.

The initial test configuration was clearly unsatisfactory. As long as the flap motion was being predominately controlled by the lead-lag actuator, it was not possible to maintain control over the flap displacement and phase angle between the flap and lead-lag displacements. To determine the best way to reduce the influence of the lead-lag forces on the flap motion of the blade, we performed a more detailed study of the forces. We created a simple kinematics model of the pushrod and bell crank using the variable definitions shown in Figure 5.

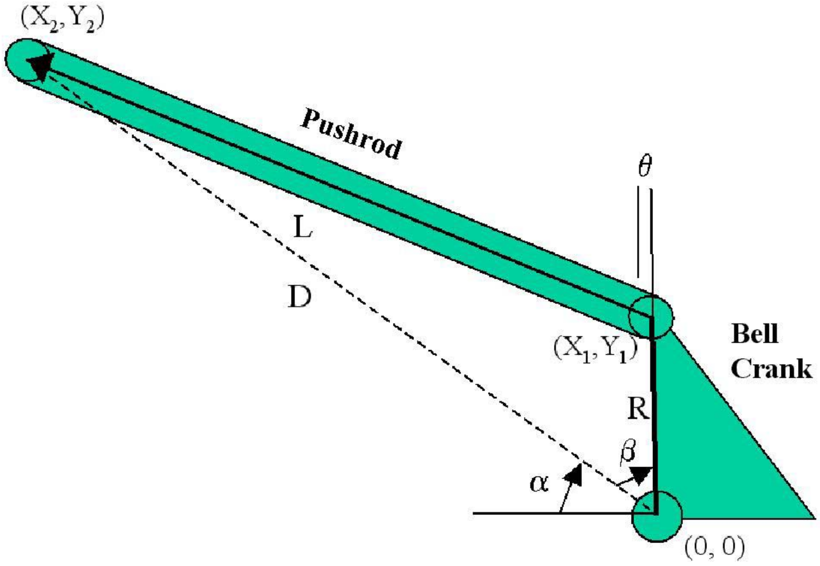

Figure 5. Pushrod/bell-crank kinematic model.

Because the lead-lag force that must be introduced by the pushrod is predetermined by the fatigue test requirements, it is convenient to describe the flap excitation forces introduced by the resonant test apparatus as a function of the lead-lag forces introduced by the bell crank. Equation 1 shows the relationship between the two forces.

$$\frac{F_f}{F_{LL}} = \frac{y_F + R - R\cos\left[90 - \sin^{-1}\left(\frac{y_F + R}{\sqrt{(x_{LL}-L)^2 + (y_F+R)^2}}\right) - \cos^{-1}\left(\frac{L^2 - R^2 - \left[(x_{LL}-L)^2 + (y_F+R)^2\right]}{2R\sqrt{(x_{LL}-L)^2 + (y_F+R)^2}}\right)\right]}{x_{LL} - L - R\sin\left[90 - \sin^{-1}\left(\frac{y_F + R}{\sqrt{(x_{LL}-L)^2 + (y_F+R)^2}}\right) - \cos^{-1}\left(\frac{L^2 - R^2 - \left[(x_{LL}-L)^2 + (y_F+R)^2\right]}{2R\sqrt{(x_{LL}-L)^2 + (y_F+R)^2}}\right)\right]} \qquad (1)$$

Where,

F_F - Flap force
F_{LL} - Lead-lag force
X_{LL} - Lead-lag blade position
Y_F - Flap blade position
L - Pushrod Length
R - Bell-crank radius

We normalized the forces to the magnitude of the lead-lag force. Figure 6 shows the dependency of the flap force introduced by the pushrod on the pushrod angle with respect to the blade. The amplitude of the flap force introduced by the pushrod is minimized when the pushrod is perpendicular to the path of flap motion while the blade is at its mean flap load position (static rest position). As shown, any deviation from this configuration results in increased flap load coupling from the pushrod.

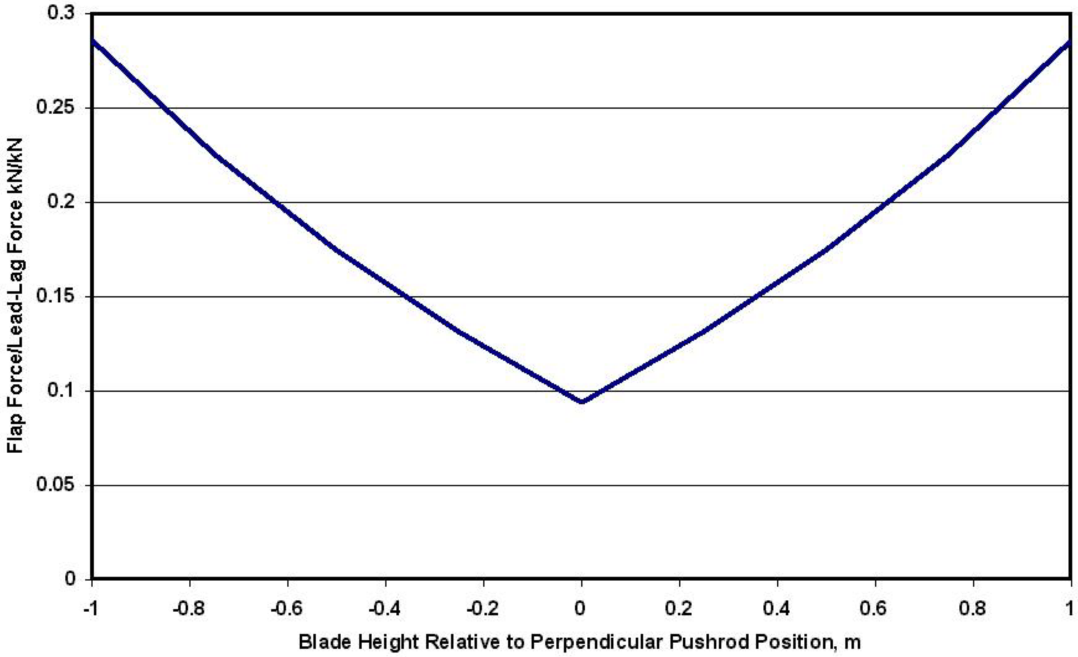

Figure 6. Influence of bell-crank orientation.

Figure 7 compares the magnitudes of the flap component of the pushrod force to the magnitude of the resonant excitation force for the configuration shown in Figure 4.

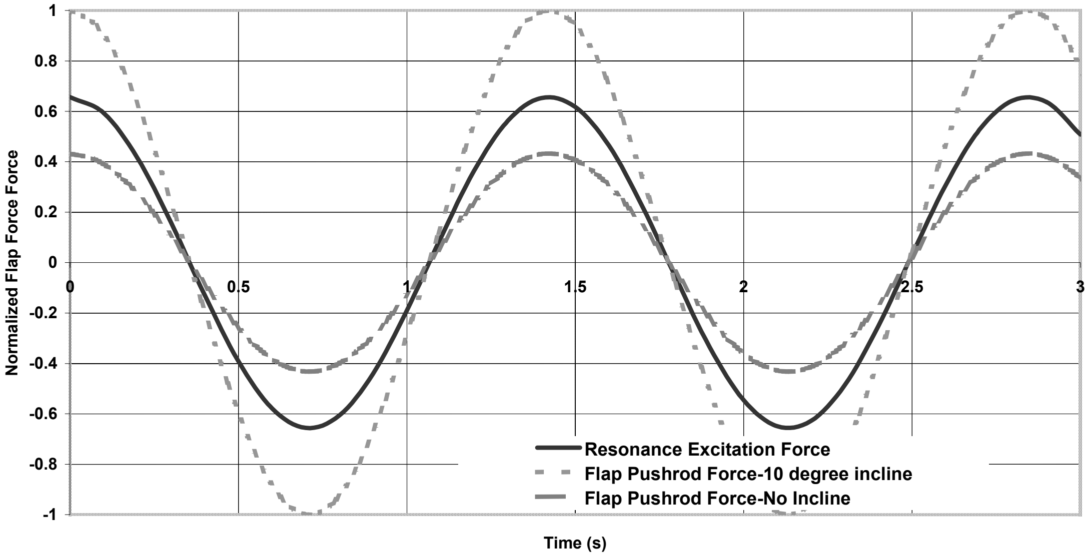

Figure 7. Comparison of flap forces from the resonance actuator and the pushrod.

The figure illustrates that the B-REX resonance excitation force is smaller than the flap force applied by the pushrod for some configurations. As shown, the flap forces resulting from the pushrod are higher than the resonance exciter forces when the pushrod is orientated in a direction that is not perpendicular to the fundamental mode shape displacement path. The flap force from the pushrod has the undesired effect of overwhelming the resonance excitation force and making the test parameters difficult or impossible to achieve for some pushrod orientations. Therefore, to minimize the influence of the bell crank in the flap direction we must carefully adjust the angle of the pushrod during the test set-up. To correct the problem, we reconfigured the test as shown in Figure 8. We changed the test-stand angle to lower the load application point of the blade. Although this change actually made the pushrod angle steeper relative to a horizontal reference, it moved the pushrod closer to a position perpendicular to the blade's flap fundamental mode displacement trajectory. The modified test configuration significantly reduced the influence of the pushrod forces on flap excitation and allowed us to conduct the fatigue test with the proper loads and load-phase angle. This empirical result is supported by the analytical results shown in figure 7, which indicate that the flap forces applied by the pushrod are smaller than the resonance excitation forces when the initial pushrod orientation is perpendicular to the displacement path of the blade. In other words, if the displacement path for the fundamental mode shape is at some angle relative to the vertical axis of the test bay, the pushrod needs to be at the same angle relative to the horizontal axis.

Figure 8. Modified bell-crank configuration.

Ultimately, the testing and analysis indicate that several of the original assumptions for developing the dynamic blade model were incorrect. In particular, we learned that it is not possible to approximate the blade dynamics using a decoupled four-degree of freedom per element beam finite element model. The coupling between the flap and lead-lag motion of the blade is integral to creating an accurate model of the test system. The coupling between the flap and lead-lag forces has forced changes in the test procedures that will be described later in this document.

IV. Test Stabilization

After we achieved the target flap and lead-lag target displacements and load phase-angle, we encountered other problems with the dynamic stability of the test.

A. Lateral Vibrations

We observed excessive lateral accelerations on the exciter apparatus at a frequency close to 3.5 Hz, which was significantly higher than the lateral driving frequency of the pushrod (approximately 0.7 Hz for this specific test specimen). These oscillations were caused by a torsional excitation of the entire test system, which includes the blade, exciter, and masses that were added to the blade to tune the flap-bending blade response and generate the target moments. Under forced hydraulic loading, dynamic effects caused by blade torsion can almost always be ignored. For the B-REX hybrid resonance system, this is no longer true. The addition of the resonant exciter and the masses to the test blade substantially lowered the blade system's torsional frequency such that the forced lead-lag loading from the pushrod induced problematic torsional motions in the blade system. Although this small displacement did not affect the fatigue test accuracy, it was severe enough to potentially damage the test equipment. Therefore, we took steps to mitigate this motion. We attached a simple system of diagnostic accelerometers to the B-REX system, so vibrations could be evaluated empirically as configuration changes were made.

We expected some lateral acceleration to result from the forced lead-lag loading apparatus determined by the inertia loading of the blade in the lead-lag axis. The minimum theoretical lateral acceleration that could be achieved for this test at 100% test load was 0.8g's or 0.8 times the standard acceleration of gravity. This value is the reference acceleration level for smooth sinusoidal loading. Initially, the observed acceleration range was over 2.0g's. The goal was to reduce the lateral accelerations to an acceptable level so the test loading could be applied without redesigning the test equipment. Although the acceptable level of vibration was subjective, based on the experience of the test engineers, the acceleration measurements provided quantitative evidence to confirm that the lowest feasible level had been achieved. Ultimately, we reduced the vibrations by 67% to a level of 1.2 g's, which allowed testing to continue. We considered this level of vibration acceptable and the test equipment has not experienced any noticeable damage. We believe that further reductions in this vibration level are achievable with a redesign of the exciter hardware system. The new system will bring the excitation mass closer to the flexure center and provide a stiffer coupling between the oscillating mass and the blade. The details of this redesign effort are beyond the scope of this paper.

We varied several different test geometry and load parameters to reduce the lateral vibration. First, we varied the derivative gain (D-gain) in the PID control system to take maximum advantage of the available control system to tame the vibrations. Changing this parameter affected the total acceleration level by about 5%, but when D-Gain was completely removed, the problem got significantly worse. Because the PID control system is relatively simple, the amount of the control flexibility was limited. Even if more sophisticated controls schemes were available, it would have been difficult to further remove the system vibration without adding capacity and cost to the actuators.

Next we modified the test geometry. Figure 8 shows that the line of action of the pushrod is below the blade section and therefore, a significant torsional moment arm existed when lead-lag forces were applied. We reduced this moment arm by raising the level of the pushrod attachment so that the line of action passes closer to the center of flexure of the test system. This had to be done without changing the angle of the pushrod relative to the blade flap motion as described earlier. We found the lateral vibrations decreased when the maximum lead-lag force went approximately through the blade systems elastic axis.

Changing the test load parameters was not a viable option for controlling lateral accelerations because changing the test load altered the fatigue loads. Nevertheless, we checked the sensitivity of both load and phase angle. The accelerations were very sensitive to the load applied. Increasing the load appeared to have a non-linear effect on the accelerations. For example, a 25% increase in load (increased from 75% to 100% of full load) resulted in a 35% change in the acceleration level.

Changes in the phase angle between the flap and lead-lag load components resulted in significant changes to the lateral accelerations. This is because the load-phase angle determines when the maximum forced lead-lag loads occur relative to the peaks in the flap displacement cycle. As the blade cycles in the flap direction, the line-of-action of the lead-lag pushrod varies with respect to the flexure center referred to earlier. If the peak occurs when the line-of-action passes through the flexure center, the excitation is small. The effects of phase angle and the problem of establishing a consistent phase-angle relationship are discussed in the following section.

B. Phase-Angle Control

Load-phase-angle control between the resonant flap load and the forced lead-lag load presented a unique problem for the B-REX test system. Recall that flap motion is controlled by careful tuning of an exciter apparatus to the eigenfrequency of the blade test system, and that the edge actuator applies forced loading at the same frequency. Under forced hydraulic loading, the phase angle is controlled directly by the servo-hydraulic controller using a fixed phase lag. Under the B-REX system the flap excitation force and the flap displacement are approximately 90° apart. In general, the load-phase angle is set using the same approach as force loading, but the phase lag must incorporate an additional 90° to account for the phase differences between the excitation and the blade response. Also, the added 90° depends on the natural frequency of the blade remaining constant, which is not always the case. As with the dynamic excitation of any mechanical system, the relationship between the excitation frequency and system eigenvalues will determine both the amplitude magnification and phase lag between the excitation force and the system response.

It has been well established that the stiffness of a composite blade will change as the blade begins to fail.[5,7,9,10] It has also been documented that the phase angle between the flap and lead-lag forces applied to a wind turbine blade has significant influence over the accuracy of the applied loads in a fatigue test.[11] As the stiffness of the test blade changes because of fatigue damage or environmental changes such as moisture and temperature, the phase angle between the blade-flap response and the lead-lag displacement will vary.

Although the change in blade stiffness observed for full-scale fatigue tests is usually small (less than 5%), the structural damping for full-scale specimens is also very small. As a result, the phase angle between the excitation force and flap displacement is very dependent on any changes in blade stiffness. Figure 9 shows that the phase angle between the excitation force and blade flap response vary if the natural frequency is changed for a fixed excitation frequency.

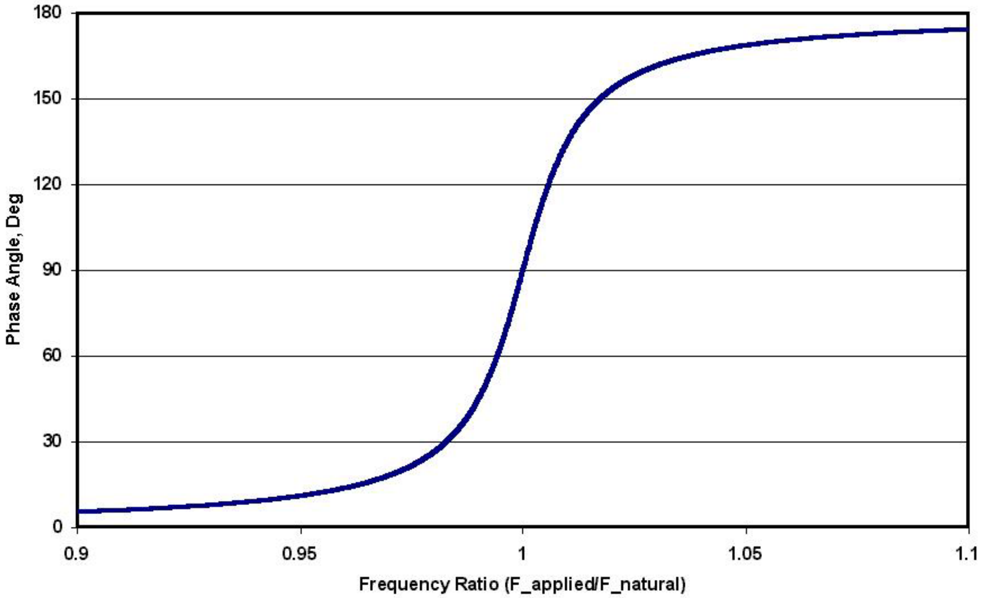

Figure 9: Influence of frequency ratio on phase angle between flap load and flap displacement.

During testing, we observed that a blade and test system experiences a 10° shift in the phase angle for a 0.010 Hz change in the excitation frequency. Similarly, changes in the blade stiffness also produced significant changes in the phase angle. Figure 10 predicts that a 5% change in stiffness will result in an 80% change in phase angle. Therefore, any change in blade properties will result in an immediate and measurable change in the phase angle.

In forced-displacement loading fatigue tests, one method for detecting blade fatigue damage accumulation is to periodically pause the fatigue test and measure the blade stiffness under quasi-static loading. If this process is not performed continuously throughout the fatigue test, damage can progress on a test specimen for a period before being noticed. Because there is a phase angle between the applied flap load and flap displacement for the B-REX test method, it is now necessary to measure this value for every cycle to monitor phase angle and determine stiffness changes. Since the phase angle is so sensitive to changes in the system, this measurement provides a more accurate estimate of any change to the test specimen compared to forced loading.

We added this measurement feature to NREL's data acquisition system called BSTRAIN[12]. The algorithm looks at the time delay between the peak-valley flap-blade displacements and flap-excitation load to determine the phase angle between the two signals. If at any time the phase angle goes outside a window of +/- 10°, the system is shut down and the blade is inspected for the initiation of damage. Experience to date is very limited and it is too early to conclude if changes in blade stiffness due to either environmental or structural effects will become a control nuisance or not.

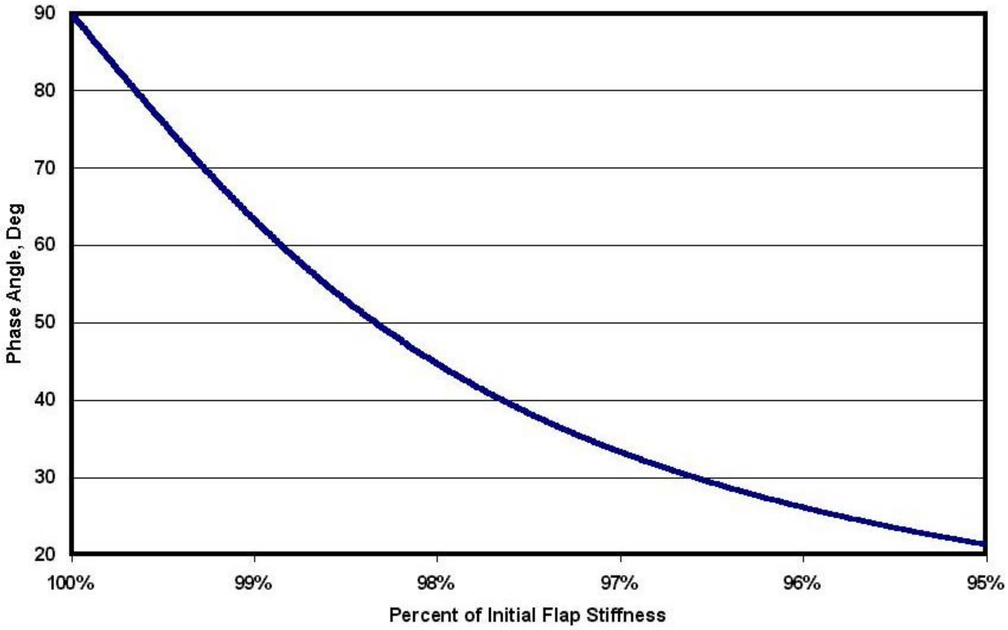

Figure 10. Influence of flap blade stiffness on phase angle

In addressing this phase-angle issue, we developed a new control and data acquisition modules that can provide additional information about the status of the specimen being testing. We are doing further evaluation to determine the accuracy of the phase-angle measurements compared to the blade damage and hopefully, this work can be correlated with other fatigue-life measuring systems.

V. Fatigue Test Results

After we resolved the issues related to the operation and stability of the resonance test system, we conducted tests to validate the accuracy of the B-REX system with respect to forced displacement tests performed on the same blade. Figure 11 shows that the blade strains from the B-REX test system agree within an acceptable range with the force-displacement test method. The strains at each location of the blade were within 3% of the forced-displacement test strains. This result also agrees with the analysis of the loads that we conducted before the test.

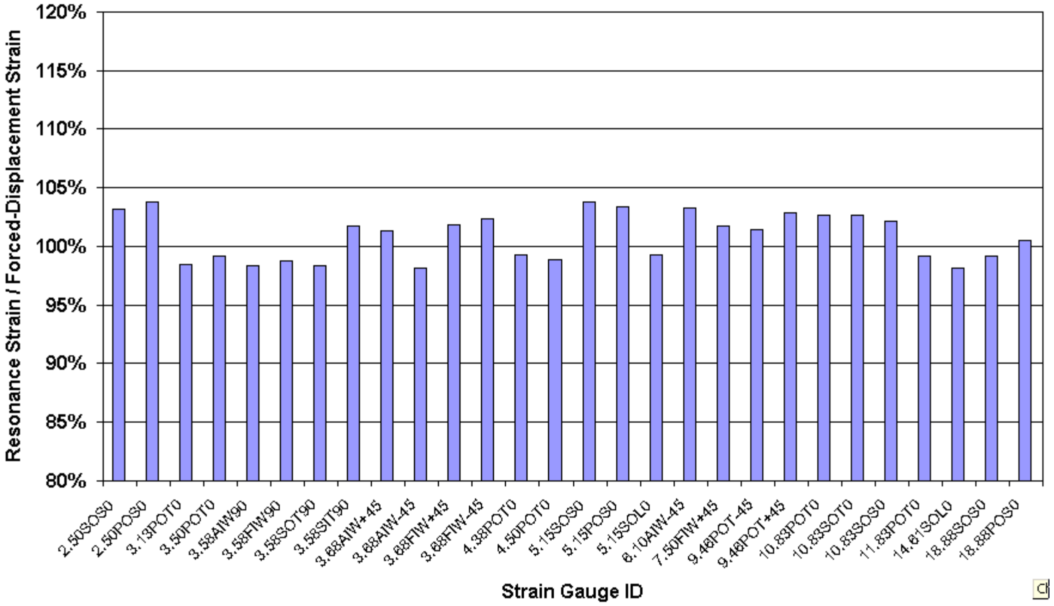

Figure 11. Comparison of strain measurements for force-displacement test and resonance test

Note that the single-point forced-displacement test system applies a linear bending moment distribution, which is not representative of the true bending moment distribution over large portions of the blade span. The resonance test system is not limited to linear moment distributions and is capable of more accurately matching actual bending moment distributions than the forced-displacement system, especially at the blade tip stations. For this test and the validation of the B-REX test method, our goal was to match the linear distribution for the forced-displacement test.

Another important aspect of the strain levels is the variation of the strain from cycle to cycle. Figure 12 shows that the strain levels over a period of 200-cycles varied approximately the same amount for both test methods and remained within an acceptable band of tolerance.

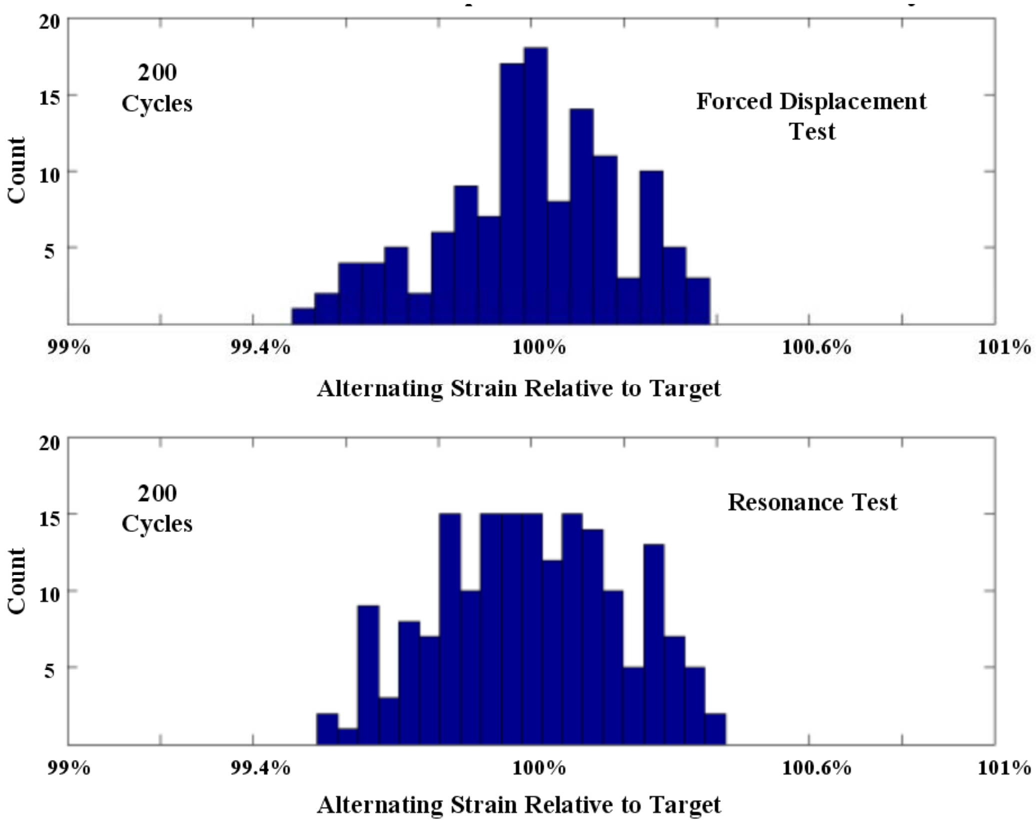

Figure 12. Example of cycle-to-cycle variation for force-displacement and resonance tests

A. Blade Displacement Verification

Under forced hydraulic loading, we used displacement transducers attached to the hydraulic actuators to infer the test loads in a relatively straightforward manner. We measured the blade position directly and fed the measurement back into the control system to maintain precise and repeatable displacement control. When loading using resonance excitation, direct measurements of displacement or load are not easily made. However, it is no less important to monitor the blade motion to maintain test stability and accuracy. Under resonance excitation, the applied forces are only a small fraction of the load required under forced loading. Therefore, the blade loads are inferred from displacements, which in turn can be calculated from measurements of the local accelerations. As such, we measured flap acceleration of the blade at critical spanwise locations using accelerometers and used the measurements for feedback control. When we compared the measured accelerations at two positions, 23-m and 28-m, along the blade to the predicted operational condition of the blade, the predicted and measured values matched closely, as shown in Figure 13. As shown, the accelerometer measurements from the resonance fatigue test system accurately compares to the predicted values.

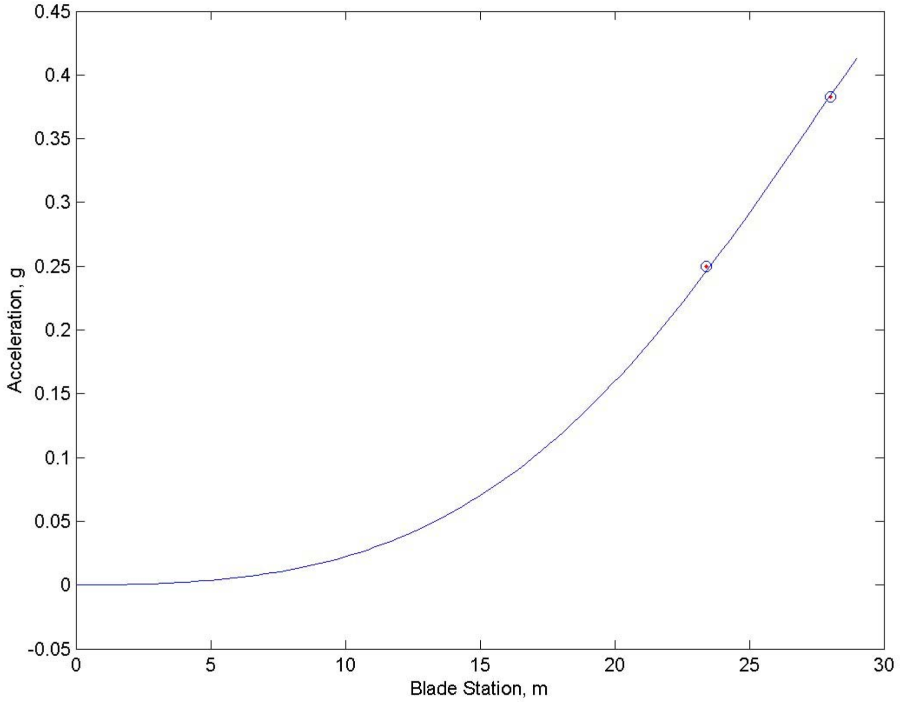

Figure 13. Comparison of predicted test accelerations and measured accelerations.

VI. Test Procedure Modifications

During the implementation of the B-REX hybrid resonance test system, several limitations and complexities of the system were revealed. Based upon these findings, we modified some of the original assumptions.

A. Revised Assumptions

- As tested, the blade approximates a slender rod (axial loads are negligible).
- Blade deflections are within the linear elastic range.
- Blade motion can be accurately described using time invariant EI values.
- Torsional blade stiffnesses are large but the added mass of the test apparatus lowers the torsional frequency enough to be excited by impulsive edge loading.
- Decoupled four-dimension per element beam FEM is NOT sufficient to model blade motion.
- Lead-lag motion is kinematically constrained by the bell crank mechanism.
- Forces applied along a predefined axis do contribute to orthogonal blade deflections.

We have established that the blade orientation for the hybrid resonance test system is much more important than it was for the forced-displacement fatigue tests. Accurate application of loads requires that the blade excitation be aligned with the trajectory of flap motion, not simply the global flap coordinates. To resolve this issue, a test blade may need to be pitched several degrees on the test stand from the blade's normal global flapwise orientation. To determine the precise rotation required for a test, we created a coupled 4-degrees of freedom (DOF) per element beam finite element model of the blade.[13] This FEM calculates the compound mode shape of the blade under excitation at the first natural frequency using local EI and mass data at several stations along the length of the blade. Combined with the local twist of the blade at each station, the model can calculate the displacements in flap and lead-lag directions. A Matlab code was written specifically for this test that uses blade specifications to determine all test parameters. including mass size, location, and pitch angle as outlined by Figure 14. This code also predicts the displacements of the blade and the natural frequency in the loaded state.

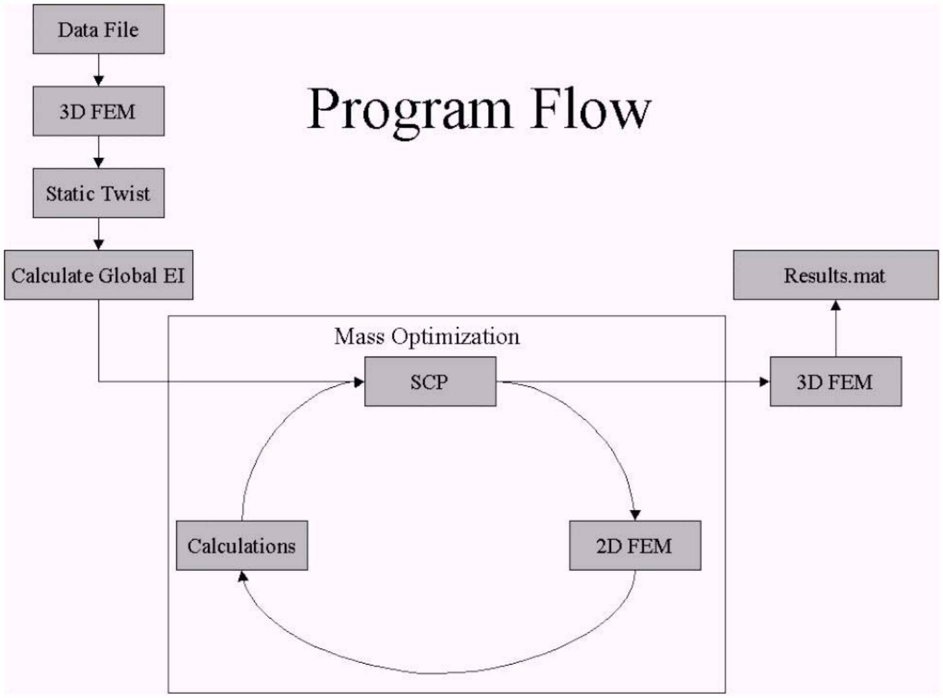

Figure 14. Modified test optimization flow chart.

The same decoupled 4-DOF beam finite element model has been used for the mass optimization because it allows the flap and lead-lag system to be considered separately.[14] The mass optimization uses sequential convex programming to determine the optimal mass size and location that achieves the best bending moment distribution along the blade. This iterative loop runs the finite element model each time it varies a test parameter, thus using the simpler decoupled 4-DOF per element beam finite element model significantly reduces computation time. Once the mass parameters are determined, the coupled FEM is run again to determine if loaded blade will require a different pitch angle than the initial analysis for the unloaded blade. For current wind turbines, the test pitch angle required did not change when the masses were added to the blade. As blades continue to get larger, it is unknown if this will be an important factor. In either case, the optimization algorithm has been programmed to evaluate the loaded and unloaded blades and recommend a target test pitch angle.

VII. Conclusions

NREL recently developed a new dual-axis test method for fatigue testing large wind turbine blades that reduces the overall test time and equipment cost compared to any existing dual-axis test system. The dual-axis B-REX test system uses resonance excitation in conjunction with forced hydraulic loading. We achieved stable operation after minimizing the flap/edge coupling dynamics. However, the analysis and testing required to implement the B-REX system was significant. From the experience in testing this new system, the following conclusions can be stated:

- The B-REX blade orientation is critical when compared to forced-hydraulic loading.
- The implementation of single-axis flap excitation using linear hydraulic actuators was very straightforward. No significant issues were associated with this portion of the test apparatus.
- Coupling from the lead-lag load apparatus into the flap motion was controlled by orienting the angle of the pushrod with the displacement path of the fundamental flap motion under free vibration.
- High torsional inertial was introduced by the resonance apparatus and caused torsional coupling with lead-lag loading. Orienting the pushrod so that its line of action passes through the flexure center of the torsional blade test system minimized the problem for the current hardware.
- To reduce the system's impact on the rotational moment of inertia, future efforts should be made to design the center of gravity of the exciter apparatus as close to the blade pitch axis as possible.

- Phase angle varies during normal testing and must be measured to accurately document the test conditions.
- Strain gage results show the B-REX hybrid fatigue test method can replicate the strain values of forced-hydraulic loading tests to within 3%.
- NREL's B-REX test system is faster by nearly a factor of 2 and uses 65% less energy than the forced-displacement loading test method.

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14. ABSTRACT *(Maximum 200 Words)*

The National Renewable Energy Laboratory (NREL) recently developed a new hybrid fatigue testing system called the Blade Resonance Excitation (B-REX) test system. The new system uses 65% less energy to test large wind turbine blades in half the time of NREL's dual-axis forced-displacement test method with lower equipment and operating costs. The B-REX is a dual-axis test system that combines resonance excitation with forced hydraulic loading to reduce the total test time required while representing the operating strains on the critical inboard blade stations more accurately than a single-axis test system. The analysis and testing required to fully implement the B-REX was significant. To control unanticipated blade motion and vibrations caused by dynamic coupling between the flap, lead-lag, and torsional directions, we needed to incorporate additional test hardware and control software. We evaluated the B-REX test system under stable operating conditions using a combination of various sensors. We then compared our results with results from the same blade, tested previously using NREL's dual-axis forced-displacement test method. Experimental results indicate that strain levels produced by the B-REX system accurately replicated the forced-displacement method. This paper describes the challenges we encountered while developing the new blade fatigue test system and the experimental results that validate its accuracy.

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