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IMPLEMENTATION OF A TWO-AXIS SERVO-HYDRAULIC SYSTEM FOR FULL-SCALE FATIGUE TESTING OF WIND TURBINE BLADES

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ABSTRACT

Recently, the blade fatigue testing capabilities at NREL were upgraded from single-axis to two-axis loading. To implement this, several practical challenges were addressed, as hardware complexity increased dramatically with two actuators applying the loads at right angles to each other. A custom bellcrank was designed and implemented to minimize the load angle errors and to prevent actuator side loading. The control system was upgraded to accept load and displacement feedback from two actuators. The inherent long strokes uniquely associated with wind turbine blade-tests required substantial real-time corrections for both the control and data systems. A custom data acquisition and control system was developed using a National Instruments LabVIEW platform that interfaces with proprietary servo-hydraulic software developed by MTS Corporation. Before testing, the program is run under quasi-static (slow speed) conditions and iterates to determine the correct operational control parameters for the controller, taking into consideration geometry, test speed, and phase angle errors between the two actuators. Comparisons are made between single-axis and two-axis test loads using actual test load data and load uncertainties are qualitatively described. To date, two fatigue tests have been completed and another is currently ongoing using NREL's two-axis capability.

INTRODUCTION

The objective of many blade fatigue tests is to verify that the as-built blade structure is capable of sustaining the full spectrum of loads it will experience during its lifetime. A typical wind turbine load spectrum may consist of more than 500 million load cycles occurring over a wide range of load amplitude ratios with significant damage occurring in both flap and lead-lag directions. To determine the test load, the design loading is compressed by increasing the load amplitude and a damage-equivalent load is computed to achieve the same total damage in a fraction of the number of cycles. [1] This is routinely achieved in theory using linear damage models such as Miner's Rule. When the analysis is complete, a greatly simplified test load is given that allows the blade to be cycled with hydraulic actuators, usually under constant amplitude sinusoidal loading.

If a single actuator is used, the loading must be further simplified to allow both the flap and lead-lag components to be applied together. Experience has shown that these simplifications can limit the accuracy of certain load-based blade fatigue tests.

Single-axis testing requires that the time-series flap and lead-lag loads be applied at the same load amplitude ratio (R ratio), where:

$$\text{R ratio} = \frac{\text{Minimum Load}}{\text{Maximum Load}}.$$

Another limitation of single-axis testing is the flap and lead-lag phase angle must be zero, or in other words, the maximum flap and the maximum lead-lag loads occur simultaneously. On operating wind turbines, the lead-lag loading tends to have a more severe reversing component, and the peaks of the flap and lead-lag operating load components are separated by a statistically varying but non-zero phase angle, with both peaks rarely occurring at the same time. The single-axis limitations are simplifications of the two-axis capabilities and the true operating environment, which increase the uncertainty of the blade test results.

Figure 1 illustrates the differences between flap and lead-lag R ratios for an actual wind turbine design load spectrum. The R ratio for each of the load cases in the wind turbine's blade design load spectrum were plotted as a function of their total damage contribution. The lead-lag design load cases are clustered about an R ratio of approximately –0.4 while the flap design load cases are clustered around a value of approximately 0.1. For a single axis test, the alternatives are to combine the loads at a compromised R ratio that is between the two clusters or to perform separate tests, one for flap and one for lead-lag. In the latter case, the flap and lead-lag loads are completely decoupled from each other, which is a non-conservative assumption. For a two-axis test, the individual load components can be applied at the nominally correct R ratio. The difference between the design and test R ratios can result in very significant material property changes on a Goodman Diagram and should be accounted for. [2]

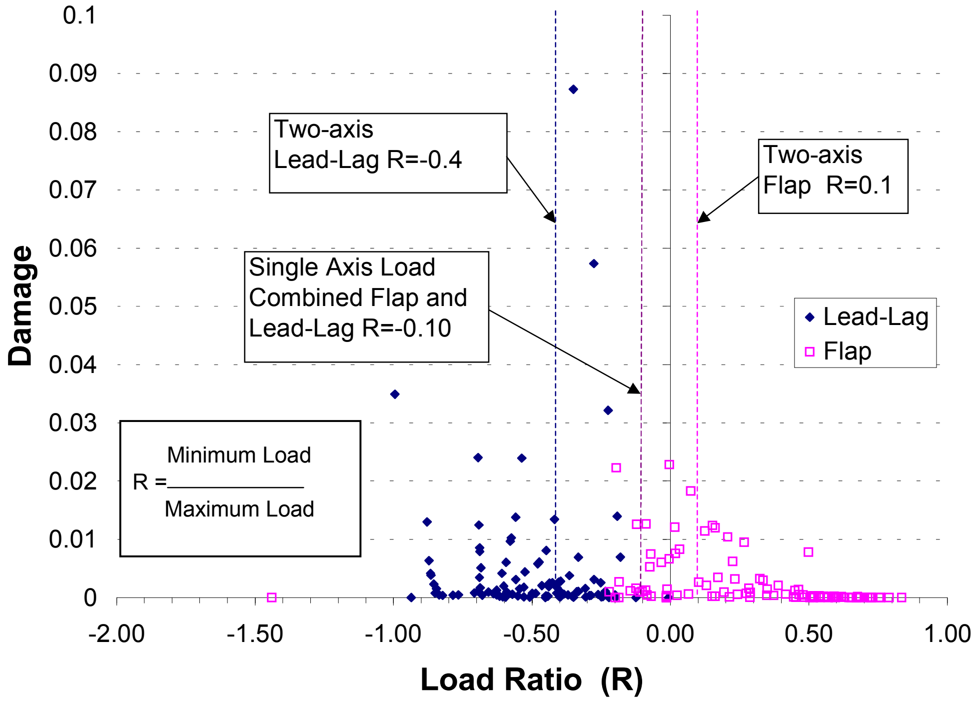

Figure 1 – Fatigue damage contribution of load cases

Figure 2 shows one cycle of a normalized single-axis test load derived from the data presented in Figure 1. An R ratio of –0.10 was chosen as the compromise between the flap and lead-lag R-ratios. Note that the resultant load reaches a maximum at the same angle as the two load components and is made significantly higher due to the effect of combining them.

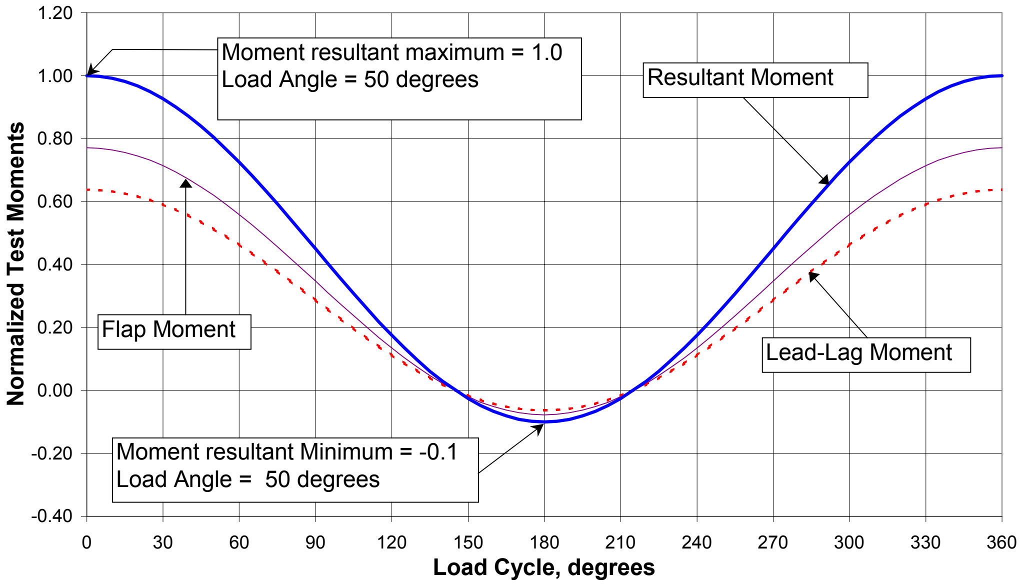

Figure 2 – Single-axis test normalized bending moment

Figure 3 shows one cycle of a normalized two-axis test load derived from the Figure 1 data. The flap and lead-lag components are no longer constrained to be at the same R ratio and the phase angle was set at a more realistic angle of 90°. Note that the normalization was done with respect to the peak resultant load in Figure 2, and the Figure 3 resultant peak is approximately 10% lower than the single-axis counterpart.

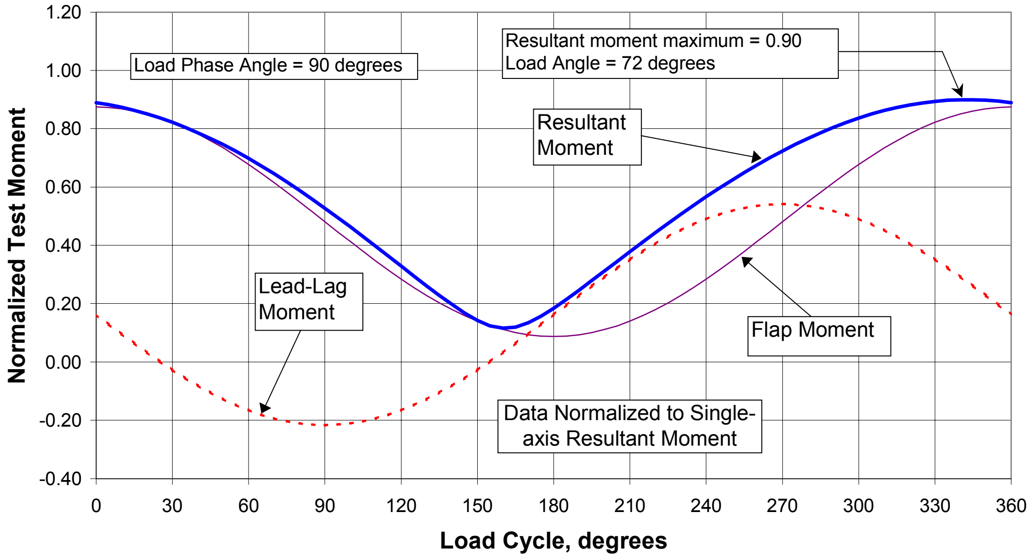

Figure 3 – Two-axis test normalized bending moment

The load angle (y) is represented in Figure 4. The resultant load angles for the two cases are shown in Figure 5. Perhaps one of the biggest differences between single-axis and dual-axis testing is seen in these resultant load angles. The load angle for this single-axis test is fixed at 50° by mounting the blade to the test stand in a pitched position.

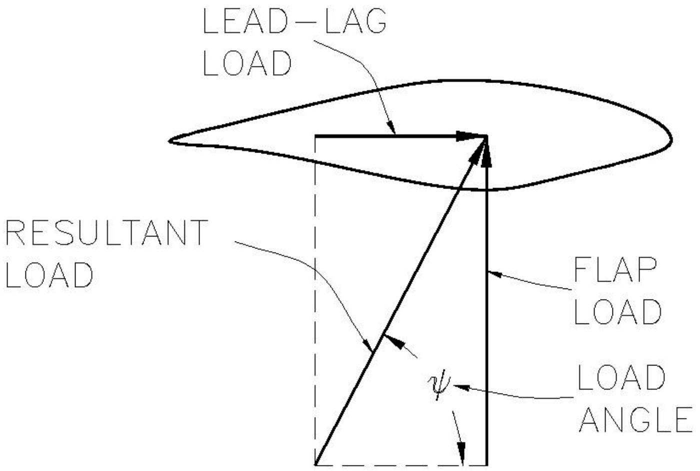

Figure 4 – Load angle diagram

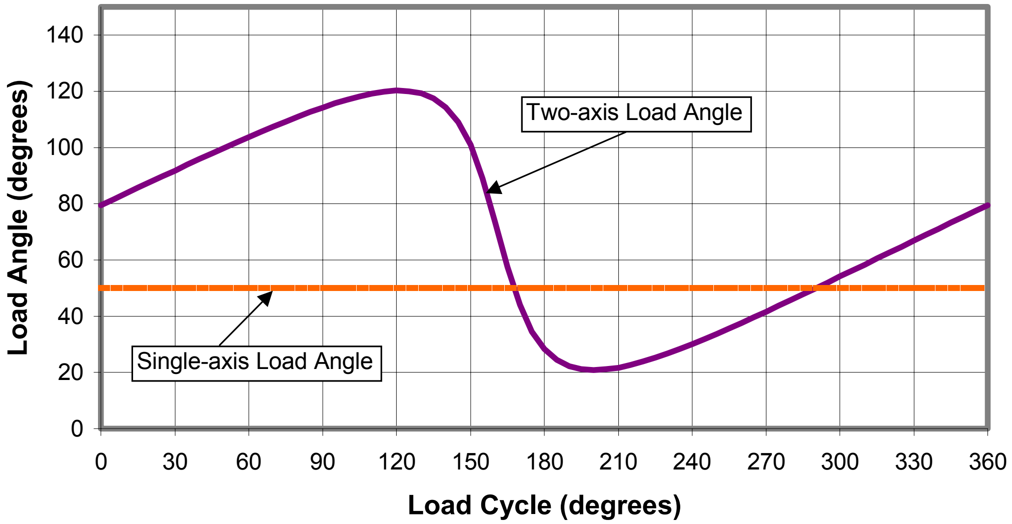

Figure 5 – Resultant load angle cyclic change for single and two-axis fatigue tests

In contrast to the non-varying single-axis load angle, the two-axis resultant load angle fluctuates from 120° to 20°. This means that a wider portion of the blade section is being stressed even though the peak loads are lower. Each of the plots shown in Figures 1 through 5 illustrate several areas where the two-axis test load more accurately represents the true operating conditions, but the complexity added to the testing apparatus is substantial. The following discussion describes the implementation of the two-axis system at the National Renewable Energy Laboratory's Structural Testing Laboratory.

HARDWARE

The two-axis testing apparatus at the NWTC is composed of four basic components: a flapwise actuator, lead-lag actuator, bellcrank assembly, and pushrod. A single hydraulic power supply is used to deliver oil to both actuators. The hydraulic power supply delivers 6.3 liters per second (L/s) (100 gallons per minute [gpm]) of oil at 20,685 kilopascals (3000 pounds per square inch). Separate hydraulic service manifolds are used for each actuator. Hydraulic service manifolds provide secondary filtration of the hydraulic oil and accumulation for both the actuator and servo-valve pilot. In addition to the accumulators contained in the hydraulic service manifold, both the pressure and return lines of the flapwise actuator are equipped with 38-liter (L) (10-gallon [gal]) bladder accumulators. A 38-liter (10-gal) pressure-side accumulator and 19-L (5-gal) return-side accumulator supplement the lead-lag actuator. The flapwise actuator and bellcrank assemblies are mounted to separate t-slot base plates. These base plates are rigidly mounted to the laboratory floor. The two-axis testing setup is shown in Figure 6. Hydraulic system components such as the hydraulic service manifold, accumulators, and the hydraulic power supply have been omitted from Figure 6 to emphasize the loading apparatus.

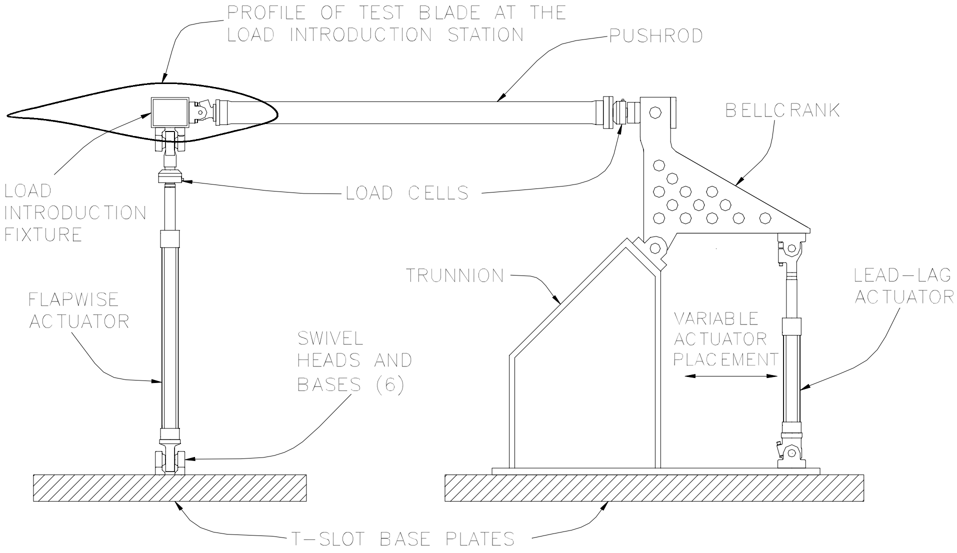

Figure 6 – Two-axis fatigue hardware schematic

The flapwise actuator setup is in general the same as used in single-axis testing. The maximum flapwise stroke is currently 127 centimeters (cm) (50 inches [in]). Flapwise actuators are capable of applying up to 111.2 kilo Newton (kN) (25,000 pounds [lbf]) tensile and 49.8-kN (11,200-lbf) compressive loads. Ends of both the flap and lead-lag actuators and the pushrod are equipped with swivel-heads. Swivel-heads allow spherical rotation, letting these members function as pinned-pinned linkages without backlash. A load cell is located at the blade end of the pushrod for measuring lead-lag forces, and at the top of the flapwise actuator for flapwise forces. Each actuator is equipped with an internal LVDT (Linear-Variable Differential Transformer), which is used to measure actuator piston displacement.

Several types of actuator configurations are possible for two-axis testing. The lead-lag loading assembly is composed of a vertically oriented hydraulic actuator mounted to the bellcrank trunnion. The trunnion provides a rigid base around which the bellcrank pivots, and it supports the actuator. The bellcrank translates the vertical displacement of the lead-lag actuator to the horizontal pushrod. The moment arm for introducing lead-lag actuator forces to the bellcrank is adjustable in 10-cm (4-in.) increments from 30.5 cm to 91.4 cm (12 in. to 36 in.), as shown on the left of the lead-lag actuator in Figure 6. This arrangement can be used to gain a mechanical advantage or minimize the stroke of the lead-lag actuator in relation to pushrod travel. The pushrod is a 305-cm (120-in.) rigid link between the bellcrank and test article. Pushrod length was designed to be as long as possible to minimize the cross-coupling effect of the flapwise and lead-lag actuators, which is addressed in the next section. The physical dimension of the testing bay limited the maximum length of the pushrod.

The bellcrank setup was chosen to eliminate side loading of the lead-lag actuator. A bellcrank configuration allows both actuators to be vertically oriented. This is advantageous because the weight of the actuator is not introducing a side load to the actuator's end cap, which houses the piston seal and bearing assembly. Removing side-loading effects extends the life of the actuator.

The lead-lag actuator is capable of applying 126.3-kN (28,400-lbf) tensile and 49.8-kN (11,200-lbf) compressive loads, with strokes up to 38 cm (15-in.). A short stroke, relative to the flapwise displacements, is adequate, as the lead-lag stiffness of the blade is typically greater than the flapwise stiffness. The lead-lag load cell is located between the bellcrank and pushrod, which removes inertial effects of the bellcrank from lead-lag load measurement.

Any phase angle between the flapwise and lead-lag loading can be achieved, but in typical horizontal axis wind turbines, lead-lag loads lag flapwise loads by 70° to 90°. Testing speed is limited by the 6.3-L/s (100-gpm) flow rate of the hydraulic power supply. Tests to date have been conducted between 0.5 and 1.25 hertz (Hz). Turbine blades are mounted via a 1.22-meter (m) (48-in.) bolt circle to a test stand fatigue-rated for a 1,356 kN-m (1,000,000 ft-lbf) root moment. (Currently a 5,423 kN-m [4,000,000 ft-lbf] test stand is being manufactured, with installation and commissioning expected for late August 1999.)

KINEMATICS

Cross-coupling is the effect of the lead-lag actuator introducing a flap load component, or the flap actuator introducing a lead-lag load component. This cross-coupling necessitates correction factors to be introduced into the test procedure. The geometric conversion used translates actuator forces into blade global flapwise and lead-lag loads. Figure 7 shows the basic kinematics and several important parameters of two-axis testing.

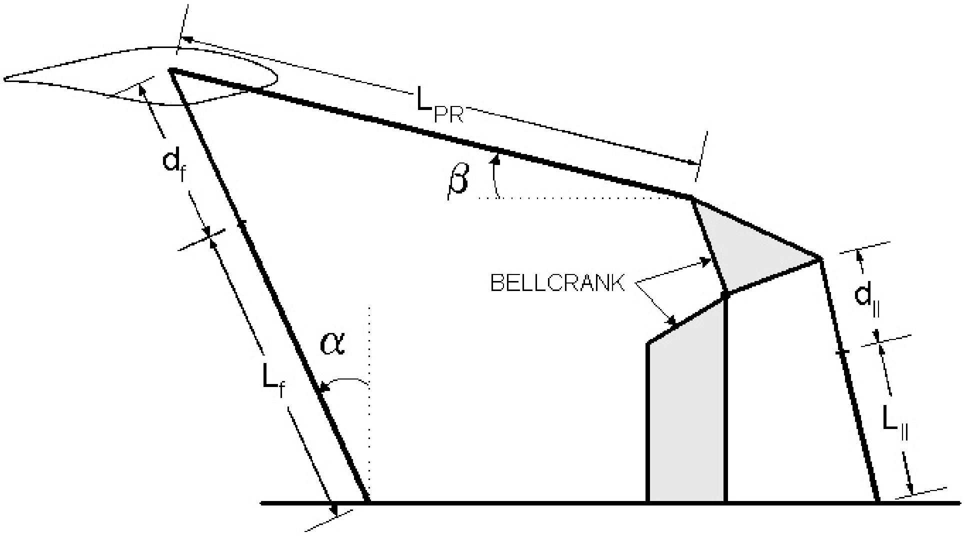

Figure 7 – Two-axis fatigue testing kinematics

Figure 7 represents the relevant kinematic components as links, showing the pistons of the actuators in an extended configuration. Subscripts (f) and (ll) denote flapwise and lead-lag, respectively. L_f and L_{ll} are the mid-stroke lengths of the actuators; d_f and d_{ll} are the actuator piston displacements. L_{pr} is the pushrod length. α is the angle the flapwise actuator makes with the laboratory vertical plane and β is the angle the pushrod makes with the laboratory's horizontal reference. The displacements of the blade, in both the flap and lead-lag frames, have been exaggerated in Figure 7 to emphasize the angles α and b. Test blades are mounted in a 0° pitch orientation, which aligns the global coordinate system of the blade with the laboratory. This allows the flapwise and lead-lag actuator force components to be defined in the laboratory reference frame. The following relationships account for cross coupling of the lead-lag and flapwise forces to obtain global (lab reference) loads:

$$
\begin{aligned}
F_{flapwise} &= F_f \cdot \cos\boldsymbol{\alpha} + F_{ll} \cdot \sin\boldsymbol{\beta} \\
F_{lead-lag} &= F_{ll} \cdot \cos\boldsymbol{\beta} + F_f \cdot \sin\boldsymbol{\alpha} \,,
\end{aligned}
$$

where $F_{flapwise}$ is the global flapwise load, $F_{lead-lag}$ is the global lead-lag load, and F_f and F_{ll} are the loads applied to the blade by the flapwise and lead-lag actuators, respectively. The second expressions in each equation are the cross-coupled terms. It can be seen from this expression how longer pushrod lengths minimize the cross-coupling effect at higher actuator displacements. The angles α and β are calculated using displacement signals from both actuators and other test geometry collected prior to the start of testing. The geometry includes a correction for the angular displacement of the bellcrank, which locates the base of the pushrod.

SOFTWARE

The custom LabVIEW-based data acquisition program BSTRAIN (Blade Structural Testing Real-time Acquisition Interface Network) was upgraded to accommodate two-axis testing. [4] BSTRAIN has been used at the NWTC for the past three years as the front-end of our data acquisition system.

In order to run two-axis tests, an additional LabVIEW-based program 2ACD (2-Axis Control Determination) was written to create corrected displacement profiles for the digital closed loop servo-hydraulic controller. The primary function of this program is to compensate for the cross-coupling effect. Blade tests are conducted using displacement control for dynamic stability. [3] 2ACD receives user inputs of loads and a phase angle to create a displacement control profile for the servo-hydraulic controller. User inputs include the maximum and minimum flap and lead-lag loads, and the phase relation between the flap and lead-lag peaks. Test geometry is also an input to the program. The program, which has control of the test via the servo-hydraulic controller, cycles the blade at a reduced rate (typically 0.1 Hz) in order to attenuate dynamic effects. Starting with initial guesses for load maxima and phase angle, the program cycles the blade for three cycles, then averages both the recorded load maxima and phase angle. Next, the control program compares the maxima with the desired loads and phases, and uses proportional gains to obtain new-time load and phase control parameters. This process is iterated until the loads and phase-angle converge within a specified tolerance. The program then creates displacement profiles for both the flap and lead-lag actuators. During actual testing the servo-hydraulic controller controls the blade, using the displacement profiles created by 2ACD. This program is run periodically throughout the test, creating new displacement parameters to account for decreasing stiffness of the blade.

As part of BSTRAIN, global stiffness values for both flap and lead-lag are recorded. Stiffness monitoring is a method to determine the health of a blade under test where large changes in global stiffness can indicate a failure in progress. At regular increments during the test (typically once per hour) the blade is cycled at a reduced frequency to obtain stiffness values and to zero strain gage scaling factors to compensate for gage drift. A reduced frequency is again used to remove dynamic effects. A decrease in stiffness can indicate declining blade. For single-axis testing, determining blade stiffness was straightforward, recording and calculating the stiffness as the load range divided by the displacement range. Two-axis testing requires BSTRAIN to account for the cross-coupling effect when calculating the blade stiffness. BSTRAIN had to be modified to calculate flap and lead-lag stiffness independently.

An autozero function is included in BSTRAIN. After the blade has been cycled at a reduced frequency, the actuators are positioned at zero-load while BSTRAIN updates the gage scaling constants to indicate zero strain.

The data acquisition program is capable of recording 48 channels of data at up to 1000 Hz per channel. Typically only peak and valley measurements are stored due to the memory requirements of storing time-series (continuous) data, but either peak/valley or time-series data may be collected.

TESTS CONDUCTED

To date, three blades have been tested using the two-axis test configuration. A Zond Z-750 blade was tested to a 30-year equivalent lifetime. Currently, another Z-750 blade from an alternate manufacturer is being tested. A Rotorline 12-m blade was tested as part of the SMT (Standards, Measurements, and Testing) program. This program was part of a round-robin blade test conducted at several testing facilities worldwide, including CRES (Greece), TU-Delft (Netherlands), ECN (Netherlands), and Risø (Denmark) to compare testing methods.

CONCLUSIONS AND FUTURE WORK

The implementation of two-axis testing at NREL has enabled more realistic fatigue blade testing to be conducted. Single-axis testing requires the test engineer to sacrifice some realism of the operating load spectrum for a reduction in system complexity, but single-axis testing is still a valuable tool for testing specific load cases or performing selected strength-based tests. Two-axis testing has several advantages over single-axis testing including introducing a phase angle between flap and lead-lag moments, a varying resultant load angle, and allowing separate “optimized” R ratios for the load components to be simultaneously applied. The drawback to two-axis testing is the considerable complexity compared with the single-axis setup. Hardware and software tools were developed to minimize the complications.

A scaled-down bellcrank and lighter pushrod will enable two-axis testing to be conducted on small-scale turbine blades.

ACKNOWLEDGMENTS

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