Experimental Modal Analysis of Research-Sized Wind Turbine Blades

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Down-scaled wind turbine blades of innovative large blade designs have undergone a full series of structural tests including modal, static and fatigue. This article provides a summary of modal testing and structural model validation. The techniques are applicable to testing of other structures.

The modal tests performed for evaluation of new wind turbine blades is the focus of this article. Major findings from these tests are highlighted and include: techniques for experimental quantification of uncertainty in the modal parameters; insight into model calibration using both static-load-deflection data and the modal parameters; novel test techniques for reducing the uncertainty in the root boundary condition using a seismic-mass-on-airbag boundary condition; and development of validated structural models.

The trend in wind energy technology continues to be larger machines with larger blades, since the technology has continued to improve and larger machines have become cost effective. Also, the capital investment for each individual wind power plant is increasing as machines become larger (and as a result of market factors as well). To address the technology needs in development of larger blades, the Sandia Wind Energy Technology Department has focused on design innovations to improve blade structural efficiency. To address blade reliability, a focus has been on validation of blade models. It is of paramount importance that new designs be developed without major systematic flaws because new designs will be fielded in large numbers in remote locations, and the capital investment per megawatt has been in the range of $1 to $2 million (U.S.) in recent years. The development of accurate predictive analysis tools, with support from the testing program, is crucial for reliability through improved modeling and simulation in design of large blades. These modal tests support these goals.

A blade development program has been underway at Sandia Labs for several years to evaluate innovative concepts in structural mechanics for wind turbine blades. These 9-meter, research-sized blades have been evaluated with static, fatigue, and free boundary condition modal tests. See Figure 1 for a sketch of the planform for each of the blades developed in this effort. The CX-100 design incorporates carbon fiber in the spar cap, as indicated in the sketch. The TX-100 blade incorporates off-axis fiber in the skins to produce bend-twist coupling. The CX-100 and TX-100 blades have identical external geometries. The BSDS (blade system design study) blade was designed with a new planform, new selection of airfoils, and a larger root diameter. Each of these three designs was modal tested at Sandia with a particular focus on the unique innovation used in each design.

Testing and modeling of the BSDS blade is the focus of this article. The BSDS blade is nominally 8.325 meters (27.3 feet) long and weighs 127 kilograms (290 lbs). A key feature in the design of the BSDS design is the use of flatback airfoils in the inboard section of the blade.

This article summarizes previously published work in a number of areas of blade testing and structural model validation.[1] The outline of the article is as follows: We first present an overview of a model validation methodology developed for wind turbine blades, which was applied to the BSDS blade. Then we discuss the modal tests and the experimental efforts to quantify uncertainty in the measured modal parameters. Next we present a hybrid calibration approach, which is used to determine the blade span-wise stiffness properties using both static and modal test data. Finally, we describe and present results from validation experiments and model development using a novel blade root boundary condition.

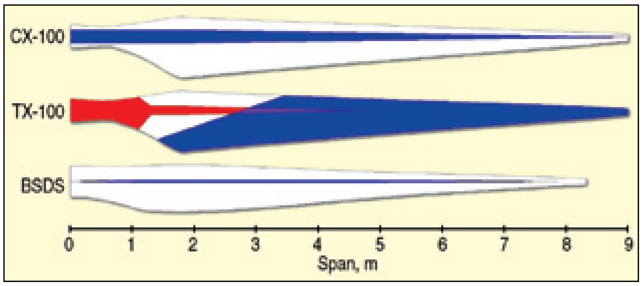

Figure 1. Research-sized blades as part of blade innovation study.

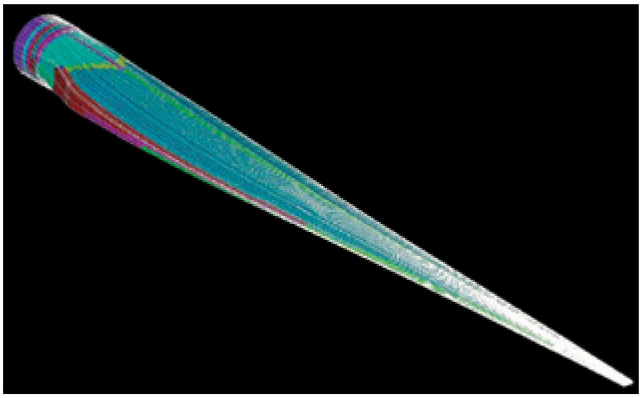

Figure 2. High-fidelity. finite-element model of a wind turbine blade.

Methodology for Blade Structural Model Validation

Model validation is a comprehensive undertaking that requires carefully designing and executing experiments, proposing appropriate physics-based models, and applying correlation techniques to improve these models based on the test data. Principal goals of model validation are to assess and improve the accuracy of a mathematical model. A methodology for rigorous blade structural model validation was presented in Reference 2, and each of the three components of model validation is reviewed in the following sections.

Experiment Design. A primary concern with any test for model validation is correspondence between the conditions of the test and the conditions of the analysis. For example, it is important that loads and boundary conditions be well characterized in a test for inclusion in the analysis. An important issue with modal testing is assessing uncertainty in the modal parameters, since test observations and analysis predictions must be compared. The decisions made in the design of the test setup are critical to validation of blade structural models. For example, the design of the instrumentation layout, the type of support conditions (boundary conditions), and choice of excitation type are important considerations in the design of a modal test. It is important to quantify the bias errors resulting from the test setup (e.g. boundary conditions and instrumentation effects) when validating models, because the bias errors can hinder suitable comparison with model predictions.

Model Development. With analysis, one is concerned with the chosen form of the model and level of detail in the model, its correspondence with the test article and the conditions of the test, and the parameters that comprise the model. The needs and capabilities

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of wind turbine blade modeling exist for levels of detail ranging from low-fidelity beam models to geometrically accurate high-fidelity, finite-element models. The decision depends on what type of analysis is needed and the availability of resources. If desired, the precise geometry of the blade airfoils, placement of materials, and internal structural geometry can be represented in a high-fidelity, finite-element model as shown in Figure 2. These types of models predict a wide range of phenomena including detailed stress contours and local buckling. Low-dimension, finite-element models, however, such as beam models, are suitable for other purposes. This type of model uses representative cross section properties and is useful for calculating, for example, deflections and natural frequencies, but does not capture the detailed local behavior of the high-fidelity model. Modal tests provide data to evaluate the chosen model form and the parameters that comprise the model.

Test-Analysis Correlation. Once tests have been conducted, models can be analyzed using the conditions (e.g., boundary conditions) of the test to make a final set of predictions to assess the credibility of the model. If the model predicts the test observations within a pre-determined adequacy criterion, then the model is considered valid for the purpose of the analysis. In many cases, however, a model does not adequately predict all aspects of the test to the predetermined adequacy criterion required for validation. Then the model is calibrated or updated by modifying the model form and/or model parameters (material properties and geometric properties) to best represent the test observations.

Updating model parameters enables one to improve the model so that it agrees with the test data; however, it must be done in a physically meaningful manner. Parameters with well known values are typically held constant; one example is the total mass of the blade, because it can be accurately measured. On the other hand, material and geometric properties typically have some uncertainty. These are the parameters one would consider varying to calibrate the model. We will later review results from our study to also use static-load-deflection test data for model calibration along with traditionally used modal test data.

Blade Testing and Experimental Uncertainty

In this section, we describe the free boundary condition modal tests and static tests that were performed to provide calibration data for the BSDS blade structural model development. A modal test of the BSDS blade was conducted using a free boundary condition, which is shown in Figure 3. The support conditions were designed to minimize their effect on the modal parameters by optimal placement and low stiffness at the two support locations using bungee cords. Experimental quantification of the uncertainty in the measured modal parameters is discussed later in this section.

The static test setup for the BSDS blade is shown in Figure 4. This test was conducted at the National Wind Technology Center (NWTC) in Golden, CO. The whiffle-tree apparatus is visible above the blade and provides the upward vertical load at three locations while the blade is constrained at the root.

From this test, deflection data were obtained as a function of the measured load input, which provides a means to calibrate the stiffness properties of the blade model. However, note that this test provided no information regarding the properties of the blade section outboard of the outer loading position, because this portion of the blade is not stressed in this loading arrangement. This is important to consider when calibrating structural models based on static tests. The uncertainties in the root boundary condition and the measured loads/deflections were not quantified in these tests.

We now turn our attention to characterization of uncertainty in experimental modal tests. Proper pretest design and test technique are critical for the validation of blade models. In Reference 3, we presented an experimental study for quantifying the uncertainty in the modal parameters for the BSDS blade. In that study, we considered test-setup uncertainty, measurement uncertainty, and data analysis uncertainty. Bias errors in the test setup were found to be the largest sources of uncertainty. The principal sources of bias error were due to the support conditions (boundary conditions) and instrumentation (mass-loading and cable damping).

Figure 3. Free boundary condition modal test of BSDS blade.

Figure 4. Static test of BSDS wind turbine blade; three-point loading shown at arrows..

Support conditions for free boundary condition modal tests can introduce large bias errors if not designed properly. For our tests, we evaluated different choices for stiffness and location of the two supports (Figure 3) and quantified the bias errors both experimentally and analytically.[4] The instrumentation was also found to be a significant potential source of bias error, particularly on the measured damping.[3]

Hybrid Calibration Method and Results

Within the framework of the validation methodology presented earlier, we now focus on test analysis correlation. In this section, we provide details on a hybrid approach for calibration of a blade structural model using both static-load-deflection data and the modal parameters.[2]

A beam finite-element model (FEM) was chosen to investigate calibration of a blade structural model. The blade span-wise mass distribution of the model was determined from measurements of a sectioned blade that had been tested to failure. With measured mass properties, the objective of the calibration was to determine the blade span-wise stiffness properties, Young's Modulus multiplied by the area moment of inertia (*EI*).

The results of different calibration approaches in this calibration study are given in Table 1; this is detailed in Reference 2. We consider three approaches for calibration of the beam model:

- Using only load-deflection data from static tests.
- Using only natural frequencies from free boundary condition modal tests.
- Hybrid approach using both load-deflection and natural frequencies.

When only static test data were used, the post calibration static-deflection residuals were small; however, predicting the first flapwise mode for a free boundary condition was under predicted by

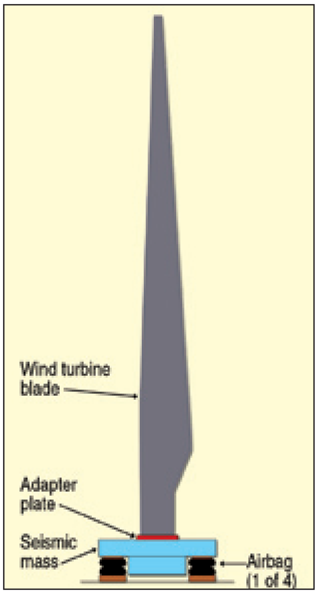

Figure 5. Schematic showing seismic-mass-on-airbag boundary condition.

12.3%. Likewise, when only natural frequency data from free boundary condition tests were used for calibration, the natural frequency was in close agreement, but the static-deflection prediction errors were large. This suggested that static test data and modal data may be used together to create a better model.

The result of the third calibration approach indicates that the residual errors can be reduced for natural frequency and static-deflection predictions. Static test data and modal data from these tests are complimentary for calibration. Static data provide key calibration data for root-end property estimates; however, in these static tests, the blade was not strained outboard of the third (outermost) load location. Free boundary condition modal tests do not result in large strains at the root; however, they do provide important data in the outboard section of the blade. Results of the hybrid approach demonstrate the benefit of combining complementary data from static tests and free boundary condition modal tests for model calibration.

Description of Validation Tests

In this section, we review the key aspects in the test design of independent validation tests performed on the BSDS blade. These tests were designed with the objective of evaluating the calibrated BSDS blade structural model. A focus of the test design was to provide a boundary condition that exercised the root while minimizing boundary condition uncertainty. The test design includes the selection of the boundary condition, test fixturing, the lift procedure, pretest model prediction, test instrumentation layout, and test execution, topics that are each discussed in Reference 5.

Again, it was essential that the boundary condition for the validation experiment be very well characterized for inclusion in the structural model. This requirement was accomplished by attaching the blade root to a seismic mass on airbags. The seismic mass is composed of steel and has a mass of 21,740 lbs (9858 kg) with dimensions of 66 inches by 72 inches (1.67 by 1.83 meters) and 24 inches (0.61 meters) thick at the thickest point. Four airbags were placed near the corners of the mass. When pressurized, the seismic mass is lifted from the floor, providing a flexible boundary condition. The natural frequencies of the six rigid-body modes associated with the seismic mass on airbags depend completely on the mass properties of the seismic mass, the stiffness properties and placement of the airbags. The schematic in Figure 5 demonstrates the approach of the test, showing the blade mounted on the seismic mass/airbag system.

A pretest analysis was performed to assist in the instrumentation layout. A 20-element FEM of the blade was used for the analysis. This calibrated blade model was then combined with a preliminary model of the seismic mass boundary condition to make predictions for the validation test. Based on the mode shapes of this model,

Table 1. Predictions of calibrated models and prediction residuals.

Calibration Type	Calibration Error for First Flap-Wise Mode with Free Boundary Conditions, %	Norm of Static Deflection Error, m
Statics updating	–12.3	0.01
Modal updating	1.1	0.31
Modal and statics updating	–1.1	0.03

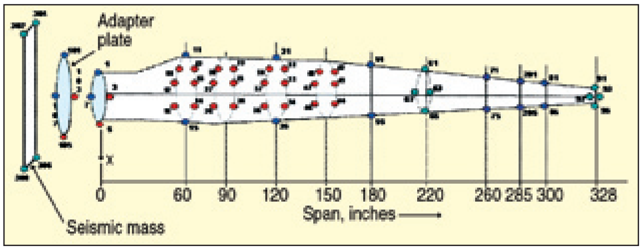

Figure 6. Instrument layout.

the span-wise layout of accelerometers was optimized for measurement of the bending modes (Figure 6). In addition to sensors placed on the blade, high-sensitivity triaxial accelerometers were placed at each of the four corners of the seismic mass to measure the rigid body motions of the blade/mass system as a check of the boundary condition. Finally, instrumentation was also placed on the root end of the blade, and additional sensors were co-located with these on the adaptor plate as a check of the rigidity of the blade connection to the seismic mass. Figure 6 shows a plot of the sensor layout. The blade was instrumented while in the horizontal position before lifting into the test configuration.

The execution of the test will now be discussed. Before the blade was placed on the seismic mass, tests were performed to characterize the modes of the seismic mass/airbag system for the airbag pressurization level and airbag placement chosen for the full system test with the blade. This test only characterized the boundary condition. We determined that a simple mass-damper-spring model with six degrees of freedom was appropriate for the boundary condition model. This model of the boundary condition was then combined with the calibrated blade FEM to make a final set of pretest predictions of the validation experiments.

With final predictions complete, a number of impact modal tests were performed on the blade with the seismic-mass-on-airbag boundary condition. A photo of the test is shown in Figure 7. More than 20 modes were measured below 160 Hz in these tests, which included rigid-body modes, flap-wise and edge-wise bending modes, torsional modes, and localized panel modes. The results for these tests focused on the flap-wise bending modes and are summarized in the following section.

Results of Validation Tests

The primary objective of the validation test was to evaluate the seismic-mass-on-airbag boundary condition for validation of a blade structural model. Mass properties measurements were used to develop an accurate mass representation for the blade FEM.[2] Then static tests and free boundary condition modal tests were conducted, and the data from these tests were then used to calibrate the stiffness properties of the blade FEM. This calibration resulted in a pretest calibrated blade FEM to be evaluated in this effort. Then a model of the seismic mass boundary condition calibrated with test data was combined with pretest calibrated blade FEM to make predictions for the combined assembly for the new test. This is a validation experiment; if the pretest calibrated blade model is valid, then our predictions with the new boundary condition should agree with the measurements according to our predetermined adequacy criterion of less than 5% error in the first 4 flap-wise bending modal frequencies. Furthermore, the results of this study will demonstrate the feasibility of this test approach for blade model validation in addition to validation of the BSDS model. The results are reported in References 5 and 6 and are summarized here.

A large set of modes was measured for comparison with the model predictions. It should be made clear that these modes represent the combined assembly of the blade and seismic-mass-on-airbag boundary condition. We are principally focused on comparing the six rigid body modes and the first 5 flap-wise bending modes of the blade system. The rigid-body-mode natural frequencies are examined first. Table 2 lists the predictions of rigid-body modes for the system using the pretest calibrated model for the blade with the seismic-mass-on-airbag boundary condition compared with the measurements from the validation test. This serves as a check of

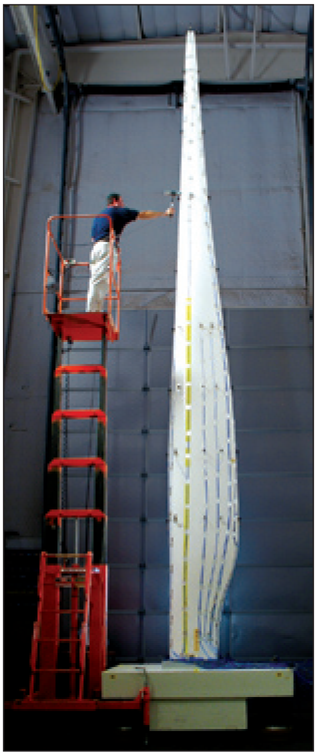

Figure 7. BSDS blade being modal tested with seismic-mass-on-airbag boundary condition.

the boundary condition model and the mass properties of the blade model. The twisting mode is in error by 3.6%, which indicates a possible inaccuracy in the mass moment of inertia of the blade model about the span-wise axis. However, this mode has an insignificant effect on the flap-wise bending modes. The pitch mode in the flap-wise direction is in error by only 1.1%, which provides certainty in this boundary condition model, since this mode most strongly affects the flap-wise bending modes.

Given that the rigid-body modes of the combined system were accurately predicted, we conclude that the boundary condition model is accurate and continue by comparing the natural frequencies of the flap-wise bending modes. This provides an evaluation of the calibrated blade model mass and stiffness properties. The pretest calibrated model was accurately predictive of the elastic blade modes, although the error in one of the first four flap-wise modes exceeded the adequacy criterion of 5%. Thereafter, a blade FEM with refined root discretization was calibrated as described in Reference 5. Table 3 lists the predictions of the flap-wise bending modes for the calibrated blade model with the seismic-mass-on-airbag boundary condition and compares them with the measurements from the validation test measurements.

Note that all errors are below 3.5%, which indicates that this model is valid for our chosen adequacy criterion. Additionally, the fifth flap-wise bending mode also meets our adequacy criterion. Note that for a free boundary condition, the first flap-wise frequency was measured at 5.25 Hz in contrast to the fixed-root boundary condition whose frequency was predicted to be 3.57 Hz. For the free boundary condition, the natural frequency is 47% higher. This demonstrates the significance of the boundary condition on the natural frequencies and the importance of accurately characterizing the root boundary condition to avoid bias error for model validation.

Discussion and Conclusions

As wind turbine blades grow longer and more costly, it is crucial that accurate predictive models be developed for use in the design phase. This article summarizes work in modal testing of research-sized wind turbine blades designed and tested at Sandia Labs. Modal tests were performed to evaluate new blade designs that incorporate innovations for blade weight reduction. A methodology for validation of blade structural models was reviewed. Then, studies related to various aspects of a model validation effort were summarized. These modal tests have resulted in;

- Techniques for experimental quantification of uncertainty in the modal parameters.
- Insight into model calibration using both static-load-deflection data and the modal parameters.
- Novel test techniques for reducing the uncertainty in the root boundary condition using a seismic-mass-on-airbag boundary condition.
- Development of a validated blade structural model.

Quantification of uncertainty in the modal parameters was performed by conducting a small number of additional experiments. The largest bias errors were due to the support conditions for free boundary condition modal tests and instrumentation mass loading and damping. A hybrid calibration approach using both modal and static test data was developed and evaluated for updating blade structural models. Traditionally, only the modal parameters are used for calibration; however, we found that static-load-deflection data can improve the calibration process. The resulting calibrated model was then evaluated by performing an independent validation modal test using the seismic-mass-on-airbag boundary condition.

The boundary condition is one of the most important considerations when performing structural dynamics analysis; any test designed to validate a structural dynamics model should provide information that well characterizes the boundary condition for inclusion in the model. A seismic-mass-on-airbag boundary condition was introduced in this test program for a blade validation modal test. The results of this work demonstrate that this boundary condition can be accurately characterized from test observations and simply modeled with properties derived from the modal parameters of the rigid-body modes.

When the blade was placed on the seismic mass, the rigid-body modes of the system and the bending modes of the blade were measured and then compared with analytical predictions of a calibrated model. This provided an evaluation of the boundary condition model as well as the blade model. This capability could be considered a new test technique for modal testing of wind turbine blades because it shows promise as an alternative to boundary conditions traditionally selected for wind turbine blade modal testing (free and fixed boundary conditions). The seismic mass boundary condition offers the advantage of the fixed boundary conditions by straining the root as in service, and it also reduces uncertainty in the boundary condition model.

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Table 2. System rigid-body modes, natural frequency: predicted versus measured.

Mode	Predicted	Measured	Percent Difference
Lateral motion flap-wise	1.08	1.08	0.0%
Lateral motion edge-wise	1.07	1.09	1.5%
Axial motion in vertical direction	1.75	1.77	1.1%
Twisting about vertical	1.80	1.86	3.6%
Pitch in flap-wise direction	1.79	1.81	1.1%
Pitch in edge-wise direction	2.26	2.22	-1.9%

Table 3. Calibrated flap-wise bending modes, natural frequency: predicted versus measured.

Mode	Predicted	Measured	Percent Difference
First flap-wise	4.05	4.20	3.5%
Second flap-wise	9.73	9.57	–1.7%
Third flap-wise	17.88	18.29	2.2%
Fourth flap-wise	29.11	29.77	2.2%
Fifth flap-wise	43.27	43.66	0.9%