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Research Article

Two Methods for Estimating Aeroelastic Damping of Operational Wind Turbine Modes from Experiments

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Key words:
horizontal axis turbine;
experimental method;
mechanical vibration

The theory and results of two experimental methods for estimating the modal damping of a wind turbine during operation are presented. Estimations of the aeroelastic damping of the operational turbine modes (including the effects of the aerodynamic forces) give a quantitative view of the stability characteristics of the turbine. In the first method the estimation of modal damping is based on the assumption that a turbine mode can be excited by a harmonic force at its natural frequency, whereby the decaying response after the end of excitation gives an estimate of the damping. Simulations and experiments show that turbine vibrations related to the first two tower bending modes can be excited by blade pitch and generator torque variations. However, the excited turbine vibrations are not pure modal vibrations and the estimated damping is therefore not the actual modal damping. The second method is based on stochastic subspace identification, where a linear model of the turbine is estimated alone from measured response signals by assuming that the ambient excitation from turbulence is random in time and space. Although the assumption is not satisfied, this operational modal analysis method can handle the deterministic excitation, and the modal frequencies and damping of the first tower and first edgewise whirling modes are extracted. Copyright © 2006 John Wiley & Sons, Ltd.

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Introduction

This article describes how to estimate the aeroelastic damping (and frequencies) of the operational modes of wind turbines from experiments. Two different experimental methods have been applied and the results are compared with theoretical predictions from the stability tool HAWCStab.[1]

Standard wind turbine testing includes estimation of the structural frequencies and damping of lower turbine modes from manual peak-picking in frequency response spectra of measured response signals, or from the decaying response after e.g. a pull on the tower or a clamping of the brake, but the estimations are only performed at standstill. Standstill frequencies and damping of the lower turbine modes are important for tuning and validation of numerical models and for verification of the prototype design. These estimated modal parameters are mostly related to the turbine structure and do not include the aerodynamic effects that dominate the aeroelastic modes of an operating turbine. Experimental methods for estimating the aeroelastic frequencies and

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damping of the lower turbine modes during operation will improve the validation of theoretical predictions and the verification of prototype designs and may also be used in health monitoring systems.

Early experiments with operating vertical axis turbines at Sandia National Laboratories have shown that it is possible to extract the natural frequencies and damping of the operational turbine modes.[2–4] In the first experiment with the Sandia 2 m turbine[2] the modal parameters are extracted by a traditional modal testing technique. A frequency response function is obtained by measuring both the response and the force from a sudden release of a pre-tensioned cable. In the later experiments with larger turbines[3,4] the size disables the application of a measurable excitation force, whereby a subspace method for model identification solely from measured response is used. In the particular subspace method used in References 3 and 4, it is assumed that the turbine has an orthogonal modal basis and that the system is time-invariant. These experiments are the first to show the potential of operational modal analysis in wind turbine testing.

When edgewise blade vibrations were observed on stall-regulated horizontal axis turbines, it initiated several theoretical analyses explaining the possibility of negative aerodynamic damping of blade modes during stall. To validate the theories and reduce the risk of such stall-induced vibrations by better prototype testing, an experimental method for estimating the aeroelastic damping of the edgewise whirling modes was developed.[5] This method is based on using a rotating eccentric mass to excite the turbine during operation at the natural frequency of a specific mode, stop the excitation and then measure the decaying vibrations at this frequency, whereby the damping can be estimated. The first experiment with the exciter method using an eccentric mass was done on a 600 kW turbine. In a later experiment with a 1·3 MW turbine[6] it is shown that variations in blade pitch angle can be used to excite the turbine through the aerodynamic forces if the size requirement of the eccentric mass makes this mechanical exciter impractical. This early work with pitch excitation shows that it is possible to excite longitudinal tower vibrations and symmetric and whirling rotor vibrations by simultaneous or cyclic pitch variations.

This article presents experiments with the pitch-regulated, variable speed NM80 prototype turbine with a rated power of 2·75 MW. The work is part of the STABCON project supported by the European Commission, where this turbine is used as test case for validation of newly developed aeroelastic stability tools.[1,7,8]

The above-mentioned exciter method was the first method used to estimate the damping of the turbine modes. The turbine is too large to be excited by a rotating eccentric mass, therefore two other types of excitation are used: pitch excitation and generator excitation by electrical torque variations. Both types of excitation can be done at a desired natural frequency; however, the forcing is quite different. Collective pitch variations at the first tower frequency were used to excite turbine vibrations related to the longitudinal tower mode, whereas variations in generator torque at the same frequency were used to excite vibrations related to the lateral tower mode. The high aerodynamic damping of the symmetric and whirling flapwise modes, together with a limitation of the blade pitch actuators of the NM80 prototype, made it impossible to achieve the required pitch amplitudes for excitation of other turbine modes with higher natural frequencies than the tower modes. Another disadvantage of the exciter method is that the excited turbine vibrations are not pure modal vibrations, especially when two natural frequencies are close as for the first two tower bending modes. This problem is shown in the article.

A second method based on operational modal analysis was therefore used to extract the natural frequencies and damping of the turbine modes solely from the response of the operating turbine due to the ambient excitation from air turbulence. Assuming that this excitation is stochastic in time and space, the method called stochastic subspace identification[9] was used to estimate a linear dynamic system that fits the measured turbine response, from which the modal parameters were then extracted. The effects of the periodic aerodynamic forcing, the periodicity of the turbine system and the closed control loop were ignored in the identified turbine model, because a commercial software package from Brüel & Kjær[10] was used, wherein these effects cannot be modelled directly. It is necessary to have many signals with many measurement points to improve the result of the model identification. The authors therefore used a sequence of several 10 min time series of seven strain gauges from load measurements for the analysis. It was thereby possible to estimate the natural frequencies and damping of the two (distinct) tower modes and the first two edgewise whirling modes. The symmetric and whirling flapwise modes have too high aerodynamic damping for identification in the response to the excitation by turbulence.

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The article is structured as follows. First, the two experimental methods are reviewed in theory to show their assumptions and limitations. Second, the experimental procedures and results are presented. The results of the two methods are then compared, followed by the conclusion.

Aeroelastic Modes of NM80

Detailed aeroelastic simulations of the turbine have been performed with the non-linear aeroelastic code HAWC[11] for the set-up of the experimental exciter method. These simulations are not included in this article; however, a presentation of the linear aeroelastic modes of the NM80 turbine is here first given as background for interpretation of the experimental results. The HAWC model is directly applicable as input for the aeroelastic stability tool HAWCStab,[1] where natural frequencies, damping and mode shapes of aeroelastic turbine modes can be computed for different operational conditions of wind speed, rotor speed and collective pitch setting.

For each eigenvalue analysis at a particular wind speed the rotational speed of the drive-train is assumed to be constant at the generator and the blade pitch angles are fixed, hence the turbine is assumed run in open loop control without the dynamics of an asynchronous generator included. A further assumption in HAWCStab is that the induced velocities from the wake are constant for each wind speed computation, even though the rotor load varies when the turbine is vibrating. Structural damping is modelled with a Rayleigh-type damping model.

The structural model is initially tuned to the lower natural frequencies measured at standstill,[12] as shown in Table I. The structural damping model is tuned to give typical logarithmic decrements for the lower turbine modes, e.g. approximately 2% for the first tower modes (estimated, not measured) and 1·5% and 1·8% for the first two blade modes (measured).

Figure 1 shows the aeroelastic frequencies and damping of the first nine turbine modes. The modes are sorted after their mode shapes which have been identified from animations and modal amplitudes. The abbreviations BW and FW refer to backward and forward whirling. The variations in aeroelastic frequencies of these turbine modes are mainly caused by the variation of rotor speed and pitch angle as the wind speed changes. The high damping of the turbine modes involving flapwise blade vibration is caused by aerodynamic damping, which also causes high aeroelastic damping of the first longitudinal tower mode.

There are four modes that are lower damped by the aerodynamic forces because the blades are moving close to the rotor plane in these mode shapes. For the first two edgewise whirling modes the BW mode is lower damped. The higher damping of the FW edgewise mode is also observed in a previous analysis of a smaller

Table I. Natural frequencies of the 10 lowest turbine modes at standstill computed with HAWCStab and estimated by peak-picking in autospectra of measured strain gauge signals

Mode no.	Mode name	Natural frequency (Hz)	
		Computed	Estimated
1	1st lateral tower	0·444	0·437
2	1st longitudinal tower	0·453	0·444
3	1st shaft torsion (free–fixed)	0·674	0·668
4	1st yaw	0·834	0·839
5	1st tilt	0·888	0·895
6	1st symmetrical flapwise	0·966	0·955
7	1st vertical edgewise	1·825	1·838
8	1st horizontal edgewise	1·862	1·853
9	2nd tilt	2·111	2·135
10	2nd yaw	2·311	2·401

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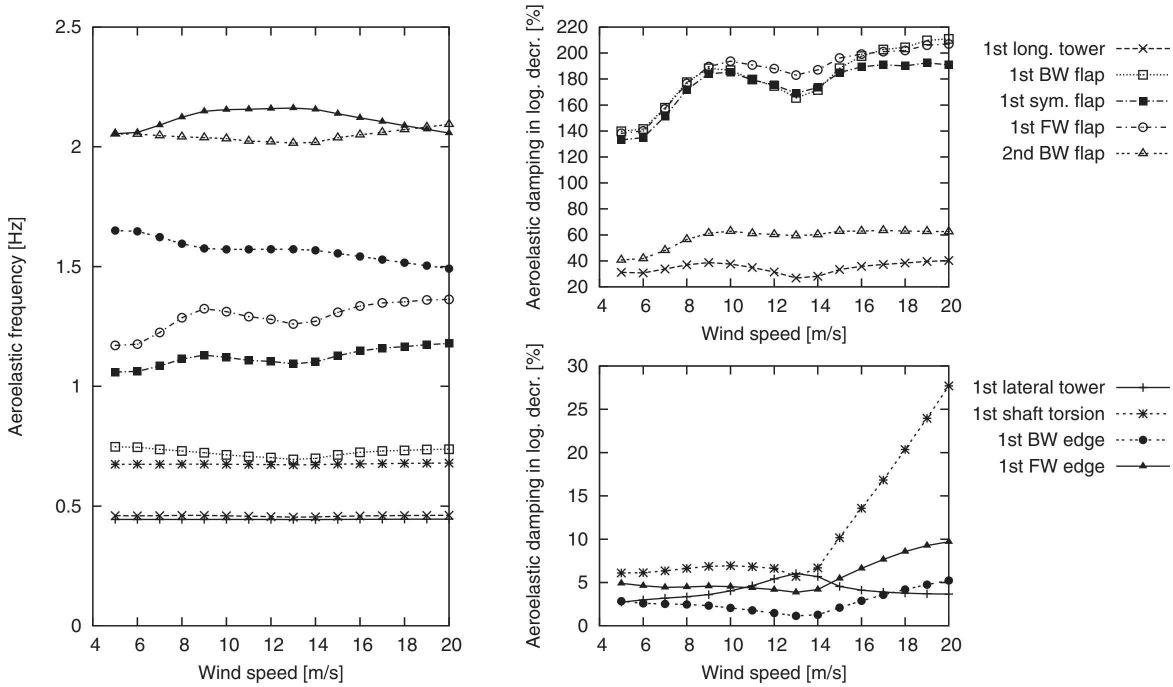

Figure 1. Predicted aeroelastic natural frequencies (left) and damping (right) of the first nine turbine modes obtained from eigenvalue analysis with the aeroelastic stability tool HAWCStab

stall-regulated turbine,[13] where it is caused by a modal interaction of the first FW and second BW flapwise modes. Note that the damping from the asynchronous generator must be added to the low aeroelastic damping of the first lateral tower and first shaft torsion modes.

Experimental Methods in Theory

This section deals with the theory behind the two methods used in the experiments. The first method described is the exciter method, where turbine vibrations are obtained by an exciter and the damping of these vibrations is estimated by analysing a decaying response after the excitation is stopped. The second method is operational modal analysis, where the natural frequencies and damping of the turbine modes involved in the response due to the stochastic excitation of air turbulence are extracted using stochastic subspace identification.

Theory of Exciter Methods

An extensive theoretical study of different excitation methods for the NM80 prototype has been performed with the aeroelastic HAWC code and reported for the STABCON project by Thomsen *et al.*[14] They showed that it is possible to excite turbine vibrations related to the first eight turbine modes (except the lateral tower mode) with pitch excitation if the three blade pitch variations have sufficient amplitudes and the right frequency (and phasing for whirling modes).

The main result of the study is a specification of the necessary pitch amplitudes to obtain a sufficient response for the different modal vibrations to dominate the stochastic response from turbulence. The excitation of the first longitudinal tower mode requires a pitch amplitude of 1° at about 0·45 Hz, the first shaft torsion requires 1° at about 0·66 Hz, the first three flapwise modes require larger than 1° at about 0·93 Hz and the edgewise

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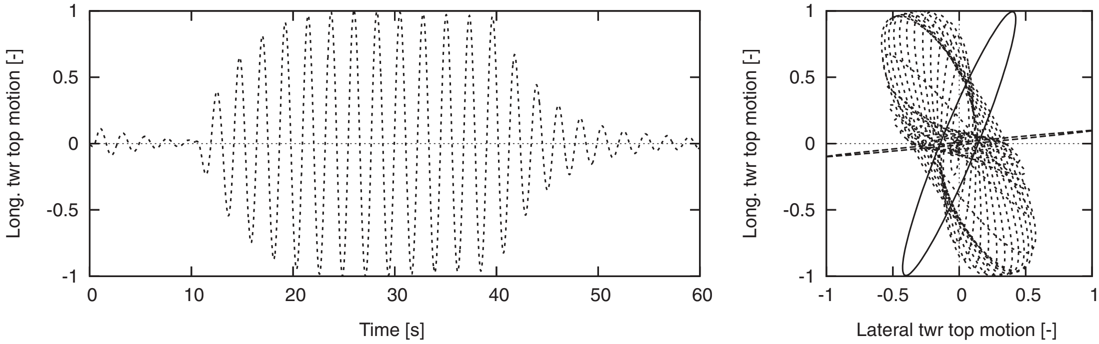

Figure 2. Simulated time series of longitudinal tower top motion (left) and the trace of the tower top motion (right) during pitch excitation (1° amplitude at 0·45 Hz from 10 to 40 s) obtained with HAWC at 15 m s^{-1} without turbulence. The two elliptic tower top traces are computed with HAWCStab for the longitudinal and lateral tower modes. All values are normalized

whirling modes require only 0·5° at about 1·8 Hz. The lower pitch amplitude needed for the edgewise whirling modes is related to their low damping, whereas the high damping of the flapwise modes made it difficult to determine the necessary pitch amplitude to produce a response that can dominate the stochastic excitation from the turbulence. The tower excitation of 1° at about 0·45 Hz equals a pitch angle acceleration of about 8 deg s^{-2}. The required pitch torque to obtain this acceleration is close to the torque limitation of the electrical pitch actuators, whereby excitation of the other turbine modes with higher natural frequencies was predicted to be impossible. Furthermore, excitation of the first shaft torsion mode will not be considered owing to active drive-train damping by the controller.

Figure 2 shows the simulated tower top motion during pitch excitation (1° amplitude at 0·45 Hz) obtained with HAWC for a wind speed of 15 m s^{-1} without turbulence. The damping estimation will in the experiment be performed from the decay of the longitudinal tower bottom bending moment, which is assumed to be proportional to the longitudinal tower top motion plotted in the left part of the figure. The right part of the figure shows the simulated tower top motion together with the elliptic traces of the tower top in the first two tower bending modes predicted with HAWCStab; note that the wind direction is from bottom to top of the figure.

Initially the tower top moves in the direction of the longitudinal excitation; however, after the excitation ends (marked by the maximum amplitude), the direction changes to be almost lateral to the wind direction. This coupling of longitudinal and lateral tower bending shows two problems with the exciter method. First, it is difficult to excite pure modal vibrations. The thrust variation due to the collective pitch variation can only excite tower vibrations in the wind direction, but the longitudinal tower mode has a 30° angle to it. Second, if two modes have nearly equal natural frequencies, vibrational energy will be transferred from the highest (longitudinal) to the lowest (lateral) damped mode, whereby the measured response decays slower than prescribed by the damping of the highest damped mode. Hence prediction of longitudinal tower damping using pitch excitation is assumed to underestimate the pure modal damping.

Variation of the electrical generator torque can be used to excite turbine vibrations related to the first lateral tower mode. Figure 3 shows the simulated tower top motion during generator excitation (2·3 kN m amplitude at 0·5 Hz) obtained with HAWC for a wind speed of 15 m s^{-1} without turbulence. Similar to Figure 2, the right plot shows the tower top trace, which in this case closely follows the elliptic trace of the first lateral tower bending mode. Thus the simulation predicts a more pure excitation with the generator of a lowest damped tower bending mode. Vibrational energy from this mode will not transfer to the higher damped longitudinal mode, and it is assumed that the decaying response of the lateral tower top motion (left plot in Figure 3) will be related only to the damping of the first lateral tower bending mode.

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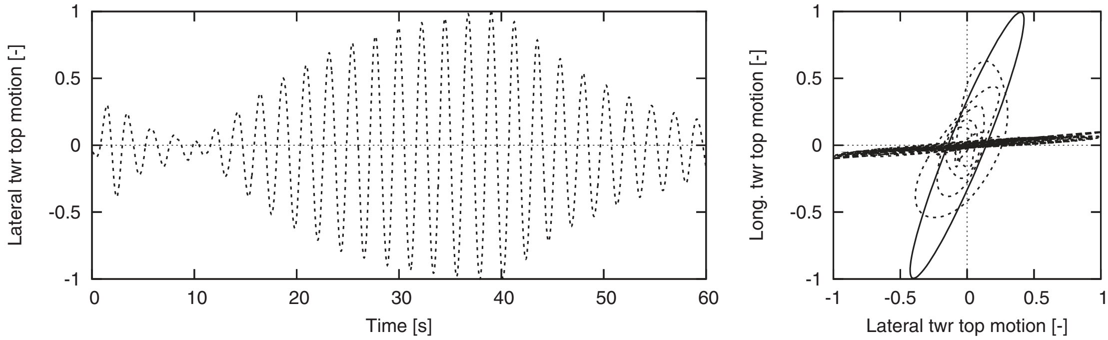

Figure 3. Simulated time series of lateral tower top motion (left) and the trace of the tower top motion (right) during generator excitation (2·3 kN m amplitude at 0·45 Hz from 10 to 40 s) obtained with HAWC at 15 m s^{-1} without turbulence. The two elliptic tower top traces are computed with HAWCStab for the longitudinal and lateral tower modes. All values are normalized

Theory of Operational Modal Analysis

Operational modal analysis (OMA) refers to methods where the excitation forces are not measured and the estimation of the modal parameters is based solely on measured response signals. One method is a model identification method called stochastic subspace identification (SSI), which is widely described in the literature, (see e.g. References 9 and 15). In this article, the SSI tools available in a commercial software package from Brüel & Kjær[10] were used.

The SSI method operates in the time domain, estimating the assumed time-invariant matrices of a linear dynamic system, which in the software package used has the form

$$\begin{aligned}\mathbf{x}_{k+1} &= \mathbf{A}\mathbf{x}_k + \mathbf{w}_k \\ \mathbf{y}_k &= \mathbf{C}\mathbf{x}_k + \mathbf{v}_k\end{aligned} \tag{1}$$

from a number of measured response signals collected in the response vector $\mathbf{y}_k$ for each instant in time with index k. The unknown dynamic states of this linear system are collected in the state vector $\mathbf{x}_k$. The states at the next instant, $\mathbf{x}_{k+1}$, are assumed to be given by the *system matrix* **A** multiplied by the present states, plus some external excitation forces $\mathbf{w}_k$. The measured response signals $\mathbf{y}_k$ are related to the states by the *observation matrix* **C**, plus some measurement noise signals $\mathbf{v}_k$. The size of the response vector $\mathbf{y}_k$ is given by the available number of measured signals, whereas the size of the state vector $\mathbf{x}_k$ must be estimated by the user. Note that the linear system (1) used in the software package does not enable the direct modelling of the closed loop control system of the turbine, which should be included in future experiments.

Once the system matrix **A** has been estimated, traditional eigenvalue analysis of linear dynamic systems can be used to compute the natural frequencies, damping and mode shapes for the state space modes. From the estimated observation matrix **C** an estimated eigenvector ϕ_i can be expressed in an observable mode shape as $\psi_i = \mathbf{C}\phi_i$. The estimation of **A** is performed for several different sizes of subspaces, whereby the repeatability of a predicted mode can be ensured.

The main assumptions in the SSI method are that the system matrix **A** and the observation matrix **C** are time-invariant and that the excitation forces $\mathbf{w}_k$ and the measurement noise $\mathbf{v}_k$ are the result of Gaussian white noise processes. With these assumptions the measured states $\mathbf{y}_k$ are used to obtain estimated states $\hat{\mathbf{x}}_k$ using a Kalman filter

$$\begin{aligned}\hat{\mathbf{x}}_{k+1} &= \mathbf{A}\hat{\mathbf{x}}_k + \mathbf{K}\mathbf{e}_k \\ \mathbf{y}_k &= \mathbf{C}\hat{\mathbf{x}}_k + \mathbf{e}_k\end{aligned} \tag{2}$$

where the vectors $\mathbf{e}_k$ are called the *innovations*, which are the differences $\mathbf{y}_k - \mathbf{C}\hat{\mathbf{x}}_k$ between the predicted and actual measurement signals. These innovations feed back into the system through the Kalman gain matrix **K**,

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thereby correcting these differences due to the two stochastic processes of excitation $\mathbf{w}_k$ and noise $\mathbf{v}_k$ in the linear system (1). Given that the estimated states have been predicted for n instances in time, the system and observation matrices can be estimated from

$$\begin{bmatrix} \hat{\mathbf{x}}_{k+1} & \hat{\mathbf{x}}_{k+2} & \cdots & \hat{\mathbf{x}}_{k+n} \\ \mathbf{y}_k & \mathbf{y}_{k+1} & \cdots & \mathbf{y}_{k+n-1} \end{bmatrix} = \begin{bmatrix} \mathbf{A} \\ \mathbf{C} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{x}}_k \hat{\mathbf{x}}_{k+1} & \cdots & \hat{\mathbf{x}}_{k+n-1} \end{bmatrix} + \mathbf{D} \tag{3}$$

by minimizing the residual **D** using a least squares method.

There are several different stochastic subspace algorithms available for obtaining the estimated states of the Kalman filter (2), which are based on singular value decomposition of a Hankel matrix of the measured response signals. Both the principal component and unweighted principal component algorithms[9] were used in the present analyses.

When selecting the measured signals $\mathbf{y}_k$ for the SSI analysis of a wind turbine, it is important to choose signals from the same frame of reference, i.e. either from the fixed frame of the tower and nacelle or from the rotating frame of the rotor. The system (and observation) matrix for a system that includes both rotor and tower degrees of freedom (states) is not time-invariant owing to the azimuthal rotation of the rotor. The other main assumption of the SSI analysis used, that the excitation is the result of a stochastic process, cannot be fulfilled. Although the turbulent inflow is close to stochastic, the resulting excitation from the aerodynamic forces will contain significant components on all P-harmonics in the rotor frame and on the 1P, 3P, 6P, etc. harmonics in the fixed frame.[16] Because the SSI method assumes that the excitation is Gaussian white noise, it interprets these P-harmonic inputs as modes in the linear system, which must be considered when the results of the linear model identification are evaluated.

Experimental Results

This section contains the results of several experiments with pitch and generator excitation performed on four different dates with different wind conditions, and the results of several operational modal analyses based on strain gauge signals measured over a 3 month period. The results are discussed based on a comparison of the two experimental methods.

Results of Exciter Methods

The control system of the NM80 prototype has been extended to include the possibilities of both pitch and generator excitation. The implementation is done so that the normal pitch and generator torque control systems can be suspended during excitation and decaying response to remove the effect of the closed loop control on the damping of the turbine modes. At the command of the operator the pitch angle and generator torque demand signals can be fixed and a harmonic variation with the desired amplitude and frequency is then added to one of these demand signals. The duration of the excitation is typically 30 s, whereafter the pitch and generator torque can again be fixed for a decaying response period of typically 10 s, until the normal closed loop control is resumed.

Ideally the turbine should run under these open loop conditions to avoid the controller changing the dynamics of the aeroelastic turbine modes. This effect is not included in the present first versions of the stability tools that are developed in the STABCON project and validated with these experiments. The rotor speed should also be constant during the decaying response period, because the aeroelastic damping depends on this parameter as well as on the wind speed. When the turbine operates in open loop, the rotor speed will vary with the wind speed and it is therefore difficult to get close to the ideal situation.

After a number of experiments it became clear that it is difficult to run the experiments for 40 s without keeping one control loop active. Most pitch excitations were therefore conducted below rated wind speed with the generator torque controlling the rotor speed. Some above rated pitch excitation experiments were also done, resulting in varying rotor speed and overspeed emergency stops. The constant mean generator torque during

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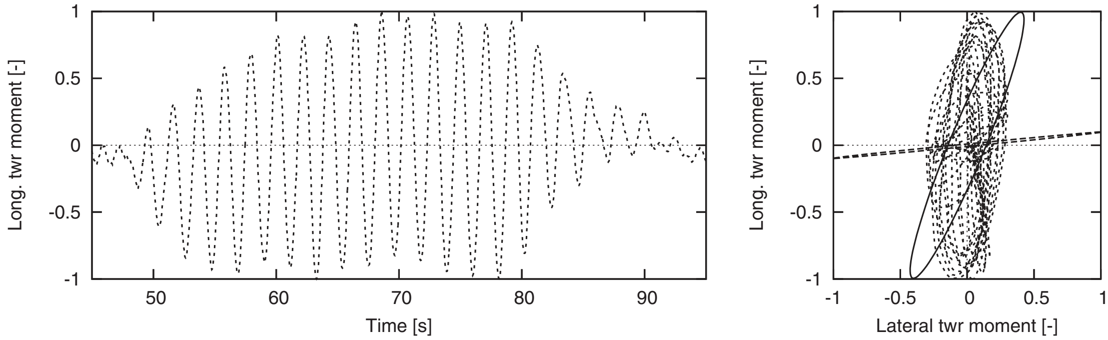

Figure 4. Measured time series of longitudinal tower bottom bending moment (left) and the trace of the two tower bottom moments (right) during pitch excitation (1° amplitude at 0·48 Hz) for a mean wind speed of about 11 m s^{-1}. The two elliptic tower top traces are computed with HAWCStab for the longitudinal and lateral tower modes. All values are normalized

generator excitation below rated wind speed resulted in rotor speed variations, because the pitch angles are kept constant. To prevent rotor speed variations during generator excitations above rated wind speed, the pitch control loop was closed, resulting in some pitch activity.

For pitch excitation of the longitudinal tower bending mode, more than 10 successful experiments were done below rated wind speed. More than seven experiments were done above rated wind speed where the rotor speed changes a lot, and some experiments have emergency stops due to overspeeds after the control loop is closed. For generator excitation of the lateral tower bending mode, 14 experiments were done, some above rated wind speed where the pitch angles vary with wind speed to prevent large rotor speed variations.

Figure 4 shows a typical example of the tower response measured during pitch excitation. The trace of the tower bottom bending moments shows that the tower vibrates in the wind direction as predicted from the HAWC simulations. The transfer of this longitudinal response into lateral tower vibrations seems to be less than predicted (see Figure 2); however, overplotting the longitudinal and lateral moments (not shown) reveals that the tower vibrates more and more in the lateral direction after the excitation stops. The difference between the simulated and measured tower responses is that the phase between the simulated longitudinal and lateral responses changes continuously during the decay, whereas this phase remains almost 180° for the measured response, causing the measured trace to open instead of changing the direction of vibration. This opening of the trace will have an effect on the damping estimated from the decaying longitudinal bending moment and therefore on the estimated aeroelastic damping of the longitudinal tower mode.

Figure 5 shows a typical example of the tower response measured during generator excitation. The trace of the tower bottom bending moments shows that the tower vibrates also in the longitudinal direction besides the excited lateral motion. The longitudinal tower excitation due to turbulent inflow can explain why the pure lateral tower vibration predicted from the HAWC simulations (see Figure 3) is not observed in the experiments. The longitudinal motion of the tower will have an effect on the damping estimated from the decaying lateral bending moment and therefore on the aeroelastic damping of the lateral tower mode.

Figure 6 shows the frequencies and damping in logarithmic decrements of the responses after the pitch and generator excitations at different mean wind speeds. The frequencies are estimated by identifying and counting the minimum and maximum amplitudes of the decaying responses of the longitudinal and lateral tower bottom bending moments (see Figures 4 and 5) and then computing the mean period of oscillation. The decrements are estimated by curve fitting an exponential function to the sequences of both minimum and maximum amplitudes and then taking the average of the two estimates of the exponent. It was often necessary to filter the time series with a bandpass filter 0·2–1·0 Hz around the tower frequency to ensure that the decaying responses were smooth functions with constant means.

The frequencies in the decaying responses are scattered around a mean between 0·46 and 0·47 Hz for both types of excitation, with significantly larger standard deviation for the frequencies after pitch excitation. The

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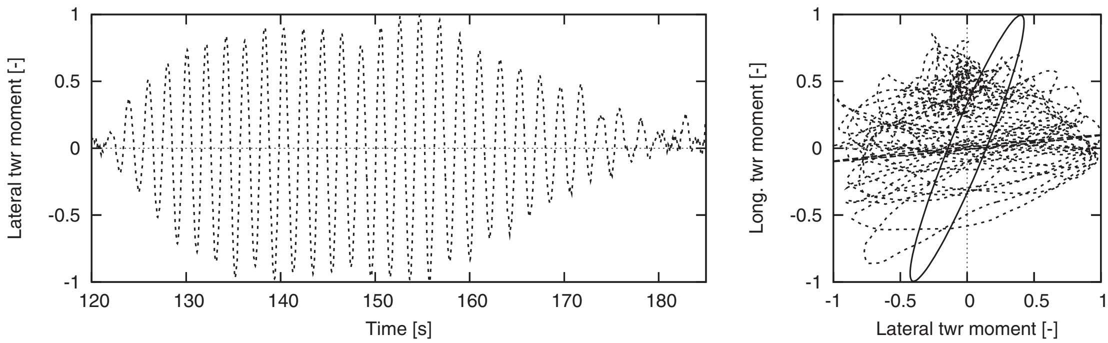

Figure 5. Measured time series of lateral tower bottom bending moment (left) and the trace of the two tower bottom moments (right) during generator excitation (2·3 kN m amplitude at 0·50 Hz) for a mean wind speed of about 9 m s^{-1}. The two elliptic tower top traces are computed with HAWCStab for the longitudinal and lateral tower modes. All values are normalized

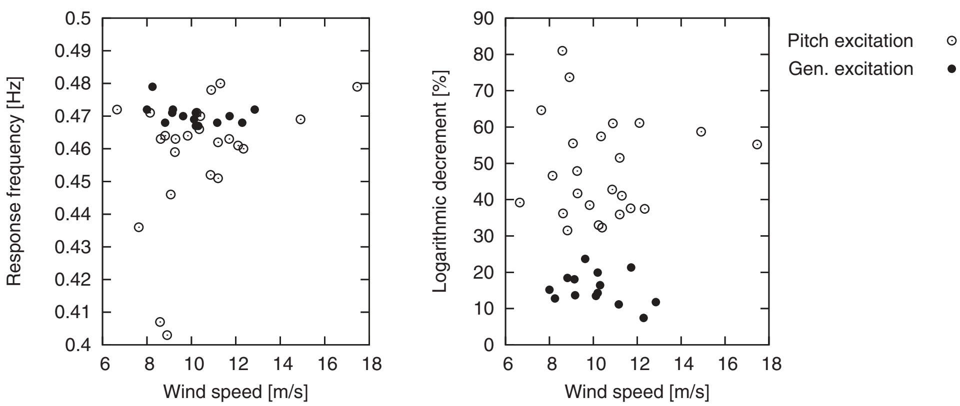

Figure 6. Frequencies (left) and damping (right) in logarithmic decrements estimated from the decaying responses after pitch and generator excitations for different mean wind speeds

scatter of response frequencies for pitch excitation is directly related to a scatter in the frequencies of the actual pitch variations that were measured during the excitation.

The logarithmic decrements of the decaying responses show that the longitudinal tower vibrations due to pitch excitations are significantly more damped than the lateral tower vibrations due to generator excitations. This observation agrees qualitatively well with both previous experiences and the predictions with HAWCStab shown in Figure 1. Again the scatter of decrements for pitch excitation is largest, which can be related to variation in response frequencies, or more likely is related to variations in the shape of the excited tower motion. A quantitative comparison between the estimated and predicted damping of the two tower modes shows that HAWCStab underpredicts the damping of both modes. A reason for the low predicted modal damping is a low drive-train damping without modelling of generator damping, because both longitudinal and lateral tower modes involve shaft/drive-train torsion.

Results of Operational Modal Analysis

The operational modal analyses using the SSI method are based on seven strain gauge signals that were measured on the tower and main shaft to compute the following loads: tower top yaw moment (direct from calibrated signal), tower top tilt and roll moments, tower bottom longitudinal and lateral moments (computed from

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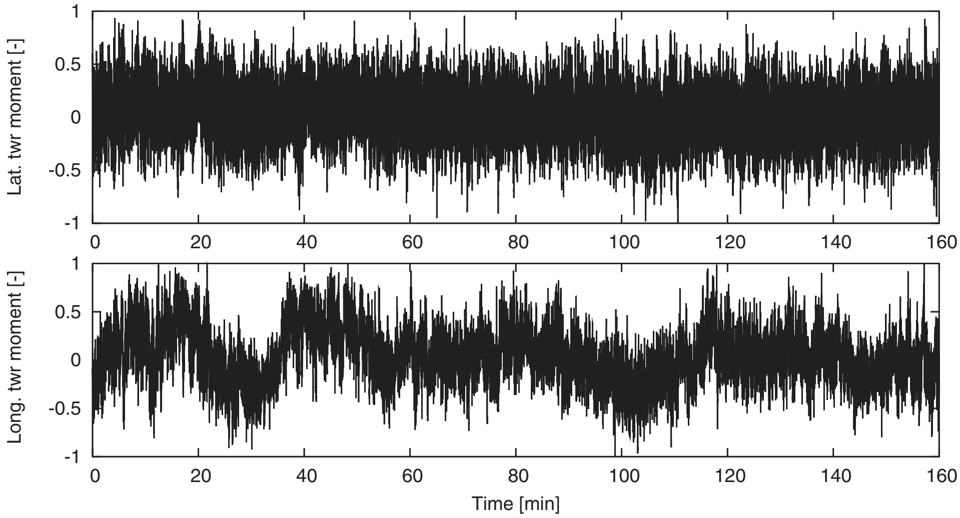

Figure 7. Examples of two measured time series for the tower bottom bending moments in the lateral and longitudinal directions used in the SSI analysis. The moments have been biased and normalized

calibrated signals and nacelle yaw angle) and main shaft tilt and yaw moments (computed from calibrated signals and rotor azimuth angle). The shaft signals have been transformed into the fixed frame of reference, where the remaining tower signals are given. The sampling frequency of these signals is 25 Hz and they are given in files with 10 min time series. About 3 months of measurements were scanned to find 1–3 h long periods of low standard deviations for wind and rotor speeds to improve the assumption of a time-invariant system in the SSI analysis. Because the turbine is operating under closed loop control, variations in wind speed will result in some pitch activity. This pitch activity will be interpreted as states in an identified dynamic system, whereby the effect of the pitch controller is included in the estimated modal frequencies and damping.

The requirement of small variations in rotor speed yields that only situations with constant minimum or maximum speed can be selected. Five periods of low wind speed and minimum rotor speed operation and 13 periods of maximum rotor speed operation in above rated wind speeds were therefore selected. Figure 7 shows examples of two measured time series for the tower bottom bending moments in the lateral and longitudinal directions used in an SSI analysis, where 16 10 min measurements have collected to almost 3 h long signals. The moments have been normalized and given a zero mean. Typically for the selected time series, there is a slow variation in the longitudinal tower moment due to variations in the mean wind speed.

The SSI analyses of the time series from all 18 measurement periods were performed and the modal frequencies and damping of the first two tower modes and the first two edgewise whirling modes were then extracted from each estimated linear system matrix. To give a qualitative picture of how good the modelled system approximates the measured system, Figure 8 shows the modelled and measured auto-spectra for the longitudinal tower bottom bending moment. The modelled auto-spectrum of this measured signal is computed from the estimated observation matrix multiplied by the estimated states of the subspace model with 48 states. The deterministic input from turbulence and rotor imbalances is clearly seen as 1P, 3P, 6P and 9P frequency components. Because the excitation is assumed to be Gaussian white noise, these components are modelled as modes in the modelled system. Fortunately, there are no coincidences with these frequencies and the actual modal frequencies when the turbine is operating at maximum rotor speed. For operation at minimum rotor speed the tower modal frequencies are close to the 3P input, and the analyses of the time series from the five periods at low wind speeds were discarded. Besides the tower modal contents, the frequency components at about 5·5P and 7·5P are identified as the first edgewise whirling modes, mainly because of their low damping and ±1P splitting around the first edgewise blade frequency. The frequency component at about 7P

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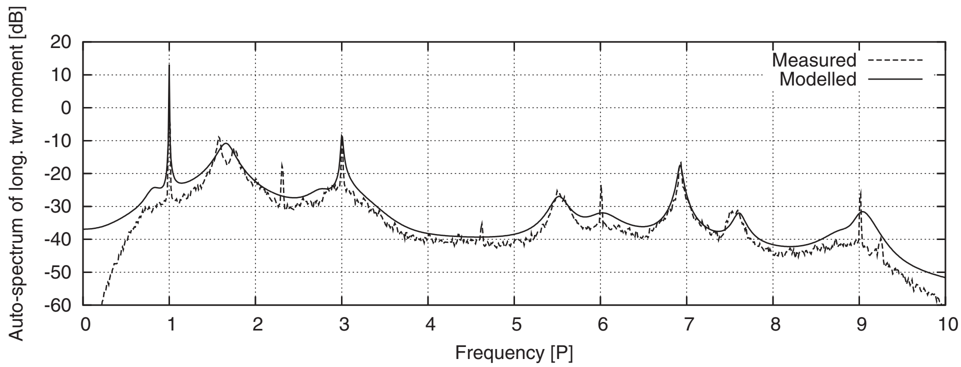

Figure 8. Measured and modelled auto-spectra for the longitudinal tower bottom bending moment, where 48 states are used in the model identification. The frequency axis is scaled with the mean rotor speed of 17·3 rpm to show the 1P, 3P, 6P and 9P inputs from the air turbulence

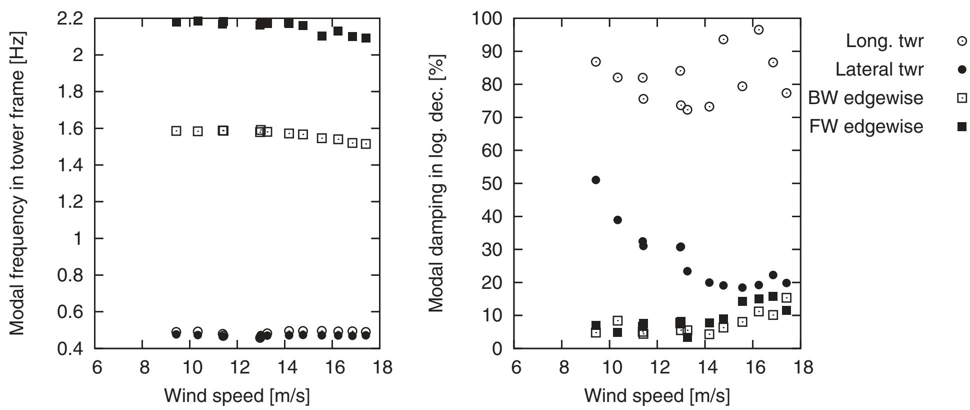

Figure 9. Estimated modal frequencies (left) and damping (right) in logarithmic decrements obtained from the operational modal analysis of measured response signals for different mean wind speeds

is the second BW flapwise mode, which has sufficiently low damping (see Figure 1) to be captured in this SSI analysis.

Figure 9 shows the estimated modal frequencies and damping of the first two tower bending and first edgewise whirling modes for the different above rated wind speeds. The estimated tower frequencies seem to be constant with wind speed; the mean ± standard deviation is 0·49 ± 0·01 Hz for the longitudinal mode and 0·470 ± 0·004 Hz for the lateral mode. The estimated edgewise frequencies decrease slightly with wind speed owing to the change in blade pitch angle above the rated wind speed. All four frequencies are very close to the aeroelastic frequencies predicted with HAWCStab (see Figure 1), where the structural HAWC model only was tuned to the standstill frequencies of the turbine.

The estimated damping of the longitudinal tower mode is scattered about a mean of 82% with a standard deviation of 8% logarithmic decrement. The estimated damping of the lateral tower mode decreases from about 50% at the rated wind speed to about 20% at higher wind speeds. For both tower modes the damping is underpredicted by HAWCStab owing to the absence of real drive-train damping in the stability analysis. The decrease in lateral tower damping for above rated wind speeds is also seen for the predicted damping.

The estimated damping of the edgewise whirling modes is below 10% logarithmic decrement, with a slight increase at higher wind speeds. There is no significant difference in the damping of the FW and BW modes as predicted with HAWCStab (see Figure 1). Again the predicted damping is lower than the estimated damping

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for the two edgewise whirling modes; however, the slightly increased damping is predicted, showing a good qualitative agreement.

Comparison of the Two Experimental Methods

The damping of the longitudinal tower bending mode estimated from the pitch excitation experiments is lower and more scattered than the damping extracted by operational modal analysis. This difference can be explained by the difficulty of exciting the pure longitudinal tower mode with the pitch excitation, whereas the SSI method estimates the modal parameters even when the two tower modes have almost equal natural frequencies. The higher standard deviations show that it is also difficult to excite the same turbine vibrations for each pitch excitation experiment.

The damping of the lateral tower bending mode estimated from the experiments with generator excitation has lower values and a different trend for changing wind speed than the modal damping extracted in operational modal analysis. The lower damping estimated from the decaying response in the lateral tower bottom moment may again be explained by an excitation of turbine vibrations other than the desired lateral tower mode. Edgewise blade vibrations will also be excited during the harmonic variation of generator torque, and the decay of this symmetric rotor vibration can feed the lateral tower motion with vibrational energy, whereby the damping is underestimated.

Conclusion

The theory and results of two experimental methods for estimating the modal damping of a wind turbine during operation have been presented. In the first method the estimation of modal damping was based on the assumption that a turbine mode can be excited by a harmonic force at its natural frequency, whereby the decaying response after the end of excitation gives an estimate of the damping. The second method is operational modal analysis based on stochastic subspace identification (SSI), where a linear model of the turbine is estimated alone from measured response due to the ambient excitation from e.g. turbulence. Modal frequencies and damping are then extracted from the system matrix of the linear model.

The main difference between the two methods is that the SSI method requires no pre-knowledge of the turbine or preparation to be applied. This method requires long time series with the turbine operating under closed loop control, whereas the exciter method gives an estimate of the damping during the short time period of the decaying response. The short time period enables open loop operation, but the exciter method cannot handle modes with almost equal natural frequencies. The closeness of the first two tower frequencies is the reason that simulations and experiments with both pitch and generator excitation of the longitudinal and lateral tower vibrations have shown that it is not possible to excite the pure tower bending modes. The damping estimated with the exciter method is therefore not the real modal damping. The operational modal analysis method estimates the real modal parameters for the operational (closed loop) turbine modes, even when their natural frequencies are close. Furthermore, the modal frequencies and damping of the first edgewise whirling modes could also be extracted with the SSI method, whereas, the pitch excitation of these modes was unsuccessful.

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