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Identification of aerodynamic damping in wind turbines using time-frequency analysis

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ABSTRACT

The paper presents a wavelet-based linearization method for evaluating aerodynamic damping of a wind turbine during operation. The method is used to estimate the aerodynamic damping solely from actual measurements of the dynamic response of the operating wind turbine due to ambient excitation from air turbulence and control forces. Based on the response measurements the generalised displacement, velocity and acceleration vectors related to a given aeroelastic model and an available aeroelastic code are estimated by a state observer. Then, the external generalised load vector, depending on the generalised velocity vector, is obtained from the aeroelastic code. Next, the external generalised load vector is linearized into two parts: a quasi-static load vector independent on the generalised velocity vector and a first order term linearly proportional to the velocity vector indicating the aerodynamic damping matrix. Filtering technique is applied to evaluate the quasi-static load vector from the actual measurements of the structural stiffness force, made up as a product of the time-dependent stiffness matrix and the estimated generalised displacement vector. Finally, the time-dependent aerodynamic damping matrix has been evaluated by wavelet analysis at each time step. Unlike other inverse-based approaches, this wavelet-based method can avoid calculating the inverse of the velocity vector covariance matrix, which is singular. The proposed method has been illustrated by a reduced 13-DOF aeroelastic model, which is used to mimic the in situ response measured on the wind turbine.

1. Introduction

Damping is the most uncertain parameter in a numerical model of a structure. It plays an important part in most dynamically-sensitive civil and mechanical structures. Characterization of damping in wind turbines is particularly complicated as the aerodynamic damping may vary with time and can even be negative depending on the aeroelastic response. The negative aerodynamic damping may lead to stall-induced vibrations in turbines, which are single mode instability in the flapwise or edgewise displacement components [1,2]. Experimental and numerical simulations have shown that these vibrations are also related to certain vibration modes of the turbine. The flapwise vibrations of the blade modes are often more

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damped than the edgewise vibrations [1,3]. Both the aerodynamic characteristics of the blade profiles and the structural dynamics of the blades influence the aerodynamic damping in wind turbines [4].

Evaluation of aerodynamic damping has primarily been based on a numerical analysis in connection with a given aeroelastic model. Based on the linear aeroelastic model, Hansen [5] carried out the Multi-blade coordinate transformation (MBC) (also known as the Coleman transformation [6]) to obtain a time-invariant representation of wind turbine system, from which the aerodynamic damping ratios were determined. Kühn [7] extended the work to consider the full non-linear property of the system. Specifically, the full non-linear system was forced into resonance at a specific eigen-frequency. Next, free-decay vibration signal was analysed to evaluate the logarithmic decrement, whereby the damping ratio can be estimated accordingly. Tempel and Salzmann [8,9] presented some more straightforward methods. They presented a formulation for the aerodynamic damping ratios for the traditional constant speed turbines and applied some aeroelastic codes to determine the aerodynamic damping value.

Alternatively, the damping may be obtained from experimental data from the operating wind turbine. Studies by James et al. [10] provided a practical approach to extract damping ratios by treating the auto- and cross-covariance function as free vibration responses. Based on set of strain-gauge signals, they calculated the auto- and cross-spectral density function of the obtained response realization. Next, the related auto- and cross-covariance functions were obtained by Fourier transformation. Finally, the poly reference time domain method [11], a kind of system identification technique based on the impulse response functions due to multiple exciter locations is applied to extract the damping ratios (both structure and aerodynamic) from the auto-covariance and cross-covariance functions which are treated as free vibration responses. Hansen et al. [12] proposed two experimental methods for estimating the aeroelastic damping. The first method is based on using two types of excitation to excite the turbine during operation at the natural frequency of a specific mode. Next, the excitation is stopped and decaying vibrations at eigen frequency are measured, whereby the damping can be estimated. The second method based on the Stochastic Subspace Identification (SSI) analysis is 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. In the study by Thomsen et al. [13], three different types of excitation were used to excite the edgewise vibration of the blade at a specific mode and stop the exciter in order to get the free-decaying signal, which contains the total damping (i.e. structure damping and aerodynamic damping) of the vibration mode. By using an exponential function to fit the decay amplitudes, they obtained the damping ratios of the considered mode.

Recently, wavelet analysis is increasingly being employed by engineers in the field of system identification, and a number of studies have been made for extracting the damping property [14–17] because of its time-frequency analysis capability and the ability to extract features from non-stationary data. Ruzzene et al. [14] proposed an approach to estimate the equivalent viscous damping ratios by taking wavelet transformation of the impulse response obtained from a viscously damped single degree of freedom system with the Morlet wavelet. The transformation results in an exponential function, which contains the damping ratio. Therefore, damping ratio can be estimated by calculating the slope of the exponential function in a logarithmic scale plot. Chakraborty et al. [15] provided a similar study where the estimation of modal damping and modal shape was carried out by using a modified L-P mother wavelet. However, most works are focused on tall buildings, transmission towers and long-span bridges [18–21]. Limited studies have been carried out in connection with the wind turbines, especially the aerodynamic damping identification. A major contribution in this field is the work of Murtagh and Basu [22], where two damping identification approaches are introduced: one which is Fourier based and the other wavelet based, primarily applicable to a multi-DOF linear structure with closely spaced modes of vibration. The first method is based on the Fourier transformation of the motion equation, by using least square method to estimate the equivalent viscous damping ratios. The second method is based on the wavelet method, using a time-segmented least square approach to extract the damping ratios.

This paper proposes a methodology for identification of the time-variant aerodynamic damping matrixes of a wind turbine using the wavelet-based equivalent linearization technique. The method presumes that the structural property matrix including the mass matrix, structural damping matrix and stiffness matrix have been obtained from a given aeroelastic code. Based on in situ measurements of the dynamic response, the external load is linearized in the generalised velocity vector to separate the aerodynamic damping force from the non-linear generalised external load vector. Finally, the aerodynamic damping matrix is identified from the aerodynamic damping force vector by a wavelet transform technique. The proposed estimation approach is particularly useful to wind turbines when the aerodynamic damping may vary with time depending on the operational conditions.

2. The 13-DOF wind turbine model

2.1. General description

The wind turbine system is modelled as a 13-DOF aeroelastic model as shown in Fig. 1. The motions of the tower and the drive train are described in a fixed, global (X_1, X_2, X_3)-coordinate, while the elastic motion of each blade relative to the hub is indicated in a moving, local (x_1, x_2, x_3)-coordinate system with its origin at the hub. The local x_1-axis is co-directional to the global X_1-axis, and the x_3-axis is orientated from the hub towards the tip of the blade. Assuming a constant nominal rota-