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Evaluation of damping estimates by automated Operational Modal Analysis for offshore wind turbine tower vibrations

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A B S T R A C T

Reliable predictions of the lifetime of offshore wind turbine structures are influenced by the limited knowledge concerning the inherent level of damping during downtime. Error measures and an automated procedure for covariance driven Operational Modal Analysis (OMA) techniques has been proposed with a particular focus on damping estimation of wind turbine towers. In the design of offshore structures the estimates of damping are crucial for tuning of the numerical model. The errors of damping estimates are evaluated from simulated tower response of an aeroelastic model of an 8 MW offshore wind turbine. In order to obtain algorithmic independent answers, three identification techniques are compared: Eigensystem Realization Algorithm (ERA), covariance driven Stochastic Subspace Identification (COV-SSI) and the Enhanced Frequency Domain Decomposition (EFDD). Discrepancies between automated identification techniques are discussed and illustrated with respect to signal noise, measurement time, vibration amplitudes and stationarity of the ambient response. The best bias-variance error trade-off of damping estimates is obtained by the COV-SSI. The proposed automated procedure is validated by real vibration measurements of an offshore wind turbine in non-operating conditions from a 24-h monitoring period.

1. Introduction

Fatigue damage accumulation during the lifetime of an offshore wind turbine generator is strongly dependent on the damping during downtime. Interpretation and analysis of the monitoring data by new real-time fault diagnosis and fault-tolerant control techniques can help the designer to improve the system reliability [1] and minimize downtime caused by malfunctioning equipment. As the wind farms are being developed at increasing water depths the transportation time from harbor to site increases, and a reduction of downtime hours is therefore not expected.

Cost effective and reliable structural designs of wind turbines are strongly dependent on the accuracy of the employed damping model. However, the system-damping matrix is often based on naive assumptions of energy dissipation phenomena. Therefore, reliable damping estimates are crucial for tuning or improving the mathematical representation of damping. In order to achieve cost effective and reliable structural designs an accurate and precise procedure for estimation of the damping is a necessity. In this paper, the reliability is sought by achieving estimates of viscous damping independent of the chosen OMA algorithm.

The vibration amplitude is governed by the amount of inherent damping present in the structures. The main sources of damping are associated with the structure, the aerodynamic and hydrodynamic interaction and the deformation of the soil by the foundation, and in some cases additional damping is provided by an external damper. Two conditions may in particular be limiting factors in the design of offshore wind turbine foundations, due to low levels of damping. The first condition is due to misaligned wind and wave loading on the structure, which cause low damping associated with side-side vibrations, while in operating conditions [2]. The second condition occurs during non-operating conditions, in which the total damping will be entirely governed by the small amount of structural and foundation damping, while the otherwise significant contribution from aerodynamic interaction is negligible. The damping in the fore-aft direction is particularly critical, as the blades are pitched out. Accurate estimation of the inherent damping is therefore an important design parameter for the next generation of offshore wind turbine structures.

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Damping has traditionally been estimated from the free decay response obtained from rotor stop tests, which is sensitive to the environmental conditions [3]. OMA enables modal identification based on ambient vibrations. In the last decade, OMA has drawn attention in connection with offshore wind turbines [4–9], despite the restrictive assumptions which these algorithms have to comply with, i.e. white noise input and linear time-invariant system. During non-operating conditions of wind turbines the vibration levels are relatively low and the assumption of a linear time-invariant system is acceptable. On the other hand, if more complex and nonlinear behavior is observed, data data-driven approaches are preferable to estimate the underlying system model [10]. Within the OMA framework, damping estimates often exhibit high variability causing skepticism concerning the physical interpretation of the results [11]. The difficulties encountered when trying to estimate damping from ambient vibrations of wind turbines has been discussed in Ref. [12]. Firstly, the successful estimation of damping depends on how realistic the underlying mathematical model of the estimation technique is. Additionally the employed procedure for automated identification also has an influence on the quality of the estimation of modal parameters. Several identification techniques have been compared, evaluated and automated for the estimation of mode shapes and frequencies, see for instance [13–19]. However there is a lack of benchmark techniques concerning the estimation of damping in offshore wind turbines, and evaluation of sources of errors related to the existing techniques which influence the quality of the estimates.

In the present paper an automated identification procedure is proposed, together with evaluation measures which indicate the type of error in the estimates of damping. To ensure algorithm independent answers three existing techniques are automated and evaluated: the ERA, the COV-SSI and the EFDD. The automated identification procedure proposed for techniques in the time domain determines the number of time lags to include in the estimation and the model order.

The variations in the estimates of damping obtained by the automated procedure are initially presented through two numerical case studies and finally applied to measured ambient vibrations of an offshore wind turbine. The first numerical study is a Monte Carlo simulation of the random response of a representative two degree-of-freedom (2DOF) system. Preliminary discrepancies in the estimates of damping are found to originate from the choice of technique and pre-processing of the response. Subsequently, the damping estimates obtained by the automated procedure are assessed for simulated offshore wind turbine tower vibrations, where the fluctuations in the tower response measurements are deliberately contaminated by signal noise. The automated procedure of damping estimation is finally demonstrated for a real offshore wind turbine in non-operating conditions from a 24-h monitoring period. From the tower top vibrations the automated procedure is able to identify the low levels of the damping in the fore-aft mode compared to the side-side mode in non-operating conditions. An extensive discussion concerning the low damping levels and improvements of the estimation techniques is provided.

2. Damping estimation from ambient vibrations

The time domain methods, ERA and COV-SSI, have been imprements following their original formulation [20,21]. An extensive review of OMA is provided in Ref. [22]. The ERA is an extension to Multiple-Input-Multiple-Output (MIMO) systems of the Ibrahim Time Domain (ITD) identification [23,24]. The data driven SSI has been shown to have properties similar to those of the COV-SSI [25] and the data driven SSI is therefore not considered in the present analysis. The objective of both time domain techniques is to estimate a discrete-time system matrix. The eigenvalue decomposition of the system matrix is interpreted as a set of discrete complex system poles. The continuous time poles are then determined as,

$$\lambda = \frac{\ln(\mu)}{\Delta t} \tag{1}$$

where μ is the discrete time pole, and Δt is the time increment. The continuous poles can be related to the natural frequency and the damping of a mode of the system,

$$\lambda = -\omega\zeta \pm i\omega_D \tag{2}$$

where i is the imaginary unit, $\omega_D = \omega\sqrt{1-\zeta^2}$ is the damped natural angular frequency, ω is the undamped natural angular frequency and ζ is the modal damping ratio. Hence, the total damping contribution is estimated by the proposed techniques. The natural frequency is thus obtained as $f = \omega/2\pi$. The eigenvectors of the discrete system matrix are interpreted as the mode shapes, which are transformed to the physical coordinates by the observation matrix.The only frequency domain technique considered in the present study is the EFDD [26], which is an adaption of the Complex Mode Indicator Function (CMIF) [27]. All the three chosen identification algorithms rely on the evaluation of the estimated correlation matrix. Such pre-processing will inevitably introduces estimation errors that propagate through the identification procedure, and in particular affect the resulting damping estimates.

2.1. Measures of performance for evaluation of estimation errors

To assess the quality of an estimate, three performance measures have been proposed. An approximation of a quantity will in the following be referred to as an estimate, while a parameter estimator will be identified by its given name, as for example ERA. Consider $\hat{\theta}$ as an estimate of θ, based on N samples of a random process. The quality of the estimate or estimator is validated in terms of the *bias* (B), the *variance* (V) and the *mean squared error* (MSE) of the realization. These are defined as,

$$\begin{aligned} B\left(\hat{\theta},\theta\right) &= E\left[\hat{\theta}\right] - \theta \\ V\left(\hat{\theta}\right) &= E\left[\left(\hat{\theta} - E\left[\hat{\theta}\right]\right)^2\right] \\ MSE\left(\hat{\theta},\theta\right) &= E\left[\left(\hat{\theta} - \theta\right)^2\right] = B\left(\hat{\theta},\theta\right)^2 + V\left(\hat{\theta}\right) \end{aligned} \tag{3}$$

where $E[\bullet]$ is the expectation operator. The variance and mean squared error are unfortunately associated with large weighting outliers due to the squaring of each term.

2.2. Pre-processing in the time domain

Bias and variance in the damping estimates using correlation driven OMA techniques have been attributed to the inclusion of the tail regions in the correlation function estimates [14]. This issue is addressed in the following. Variability on the choice of correlation function estimate has been found in literature [22,28]. Therefore, two types of correlation function estimates have been considered: an unbiased and a biased estimate. The general expression of the correlation function for ergodic *wide-sense stationary processes* $X(t)$ and $Y(t)$ is

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