Dynamic Characterization of Operational Wind Turbines using Operational Modal Analysis

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Abstract

Experimental dynamic characterization of a wind turbine, operating under variety of conditions, is a desired task as it provides useful insights that can be used for number of tasks including design optimization, validation and verification of aeroelastic and finite element codes and development of an optimal control system. However, current state of art experimental techniques are insufficient to overcome the challenges posed by a wind turbine structure. Operational Modal Analysis (OMA) is a recent technique that aims at estimating the dynamic characteristics of a structure on the basis of measured responses of the structure to ambient excitations. OMA emerges from the needs in the application field of civil infrastructure and though its ability to characterize huge and complex structures (like bridges, stadiums, buildings etc.) makes it extremely attractive for application to wind turbines as well, there are certain issues which prevent its straightforward application to wind turbines. These issues include time variant nature of the wind turbine, presence of considerable aeroelastic effects in the excitation, presence of harmonic components in the excitation etc.

The goal of this paper is to address these issues in order to make OMA more applicable and suitable for wind turbines. The paper first shows the application of OMA to a parked turbine and then subsequently shows its application to operational wind turbine. It is demonstrated how incorporating techniques like Coleman transformation and proper test planning, OMA can act as a viable tool for characterizing the dynamics of an operational wind turbine.

Keywords: Operational Modal Analysis, Coleman Transformation, Dynamic Characterization, Aerodynamic forces.

1. Introduction

Dynamic characterization of a structure is often done in terms of its modal parameters i.e. modal frequency, damping and mode shapes. Operational modal analysis (OMA) is a technique for estimating modal parameters of structures only on the basis of measured output responses [1]. This technique is well suited for large and complex structures that are difficult (even impossible) to excite artificially and hence are more suited for a technique like OMA that utilizes the response of such structures to natural ambient excitation. Thus OMA has found successful application to civil infrastructure like buildings, bridges and stadiums, where wind and rain provides for natural excitation.

These factors form the motivation of utilizing OMA for dynamic characterization of wind turbines. Dynamic characterization of a wind turbine based on experimental techniques such as OMA, is of considerable importance. It can not only improve the dynamic behaviour of the turbine by means of a better design but also aid in validating various numeric codes used for designing a turbine (such as finite element codes, aeroelastic models, control system design codes, etc.). This is bound to improve performance of the turbine and increase its efficiency and overall life.

Successful application of OMA depends on the adherence of the structure and the natural forces exciting it on certain assumptions. These assumptions are: 1) The structure should behave linear, time invariant, and 2) The excitation forces should be random, broadband and uncorrelated in the frequency range of interest. Traditionally, wind excitation is considered as a perfect excitation obeying the OMA assumptions and hence OMA seems an ideal candidate for identifying dynamic characteristics of a wind turbine. However, the present study shows that the aeroelastic phenomena, due to rotor rotation, and time-varying nature of wind turbine during operation, sets limitations on the applicability of OMA to operational wind turbines. Based on these results, possible methodologies are suggested and discussed to deal with these limitations and make OMA applicable to wind turbines.

The paper is organized in the following manner. Section 2 introduces the basic fundamentals of operational modal analysis. Section 3 shows the application of OMA on parked turbine. This is followed by discussion of limitations posed by the wind turbine structure and nature of aerodynamic forces on the applicability of OMA to operational wind turbines in Section 4. In this regard, the concept of Multiblade Coordinate Transformation, along with other methods, is presented to overcome these limitations. Finally, conclusions are made along with directions for future research.

2. Operational Modal Analysis: Theoretical Background [1, 2]

As mentioned before adherence to basic assumptions is the key to successful application of OMA techniques. Importance of these assumptions can be gauged by the fact that modal parameters obtained using OMA are obviously affected depending on how closely the actual conditions resemble the one supported by these basic assumptions. These assumptions are listed below:

1. Power spectra of the input forces are assumed to be broadband and smooth;
2. The input forces are assumed to be uncorrelated;
3. The forces are distributed over entire structure

In other words, the excitation is assumed to be randomly distributed both temporally and spatially.

Eqn. (1) gives the mathematical relationship between the vector of measured responses, $\{X(\omega)\}$ and vector of input forces, $\{F(\omega)\}$ in terms of the frequency response function (FRF) matrix [H(ω)] [3]:

$$\{X(\omega)\} = [H(\omega)]\{F(\omega)\} \tag{1}$$

Taking Hermitian of Eqn. 1 and multiplying with itself

$$\{X(\omega)\}\{X(\omega)\}^H = [H(\omega)]\{F(\omega)\}\{F(\omega)\}^H [H(\omega)]^H \tag{2}$$

and applying averaging, yields

$$[G_{XX}(\omega)] = [H(\omega)][G_{FF}(\omega)][H(\omega)]^H \tag{3}$$

where $[G_{XX}(\omega)]$ is the matrix of output power spectra and $[G_{FF}(\omega)]$ is the input force power spectra matrix.

From the first two assumptions, it follows that

$$[G_{FF}(\omega)] \propto [I] \tag{4}$$

therefore the output power spectrum $[G_{XX}(\omega)]$ is proportional to the product $[H(\omega)][H(\omega)]^H$ and the order of output power spectrum is twice that of the frequency response functions. Thus $[G_{XX}(\omega)]$ can be expressed in terms of frequency response functions as

$$[G_{XX}(\omega)] \propto [H(\omega)][I][H(\omega)]^H \tag{5}$$

Partial fraction form of G_{XX} for particular response locations p and q is given as

$$G_{pq}(\omega) = \sum_{k=1}^{N} \frac{R_{pqk}}{j\omega - \lambda_k} + \frac{R^*_{pqk}}{j\omega - \lambda^*_k} + \frac{S_{pqk}}{j\omega - (-\lambda_k)} + \frac{S^*_{pqk}}{j\omega - (-\lambda^*_k)} \tag{6}$$

where R_{pqk} and S_{pqk} are k^{th} mathematical residue terms which in contrast to FRF based model do not contain modal scaling information (since input force is not measured). It is important to note that this expression shows that power spectra contains all information needed to define the modal model of the system (except for modal scaling factor), provided the loading assumptions are true.

3. OMA Application on a Parked Turbine

The virtual turbine used in present analysis is the 5MW machine designed by Jonkman [4] as a numerical reference turbine. The modeling and simulations are performed using the nonlinear aeroelastic multi-body code called HAWC2 [5]. This simulation tool provides with the simulated response accelerations in all three directions at 25 locations on the turbine; 10 on the tower and 5 each on the three blades. Tower measurements are done at a height of 10, 20, 30, 40, 50, 60, 70, 80, 90 and 99.5 m from the base. Blade measurements are at a radial distance of 1.0, 8.33, 28.15, 48.65 and 63.0 m. 200 minutes of data is collected at a sampling rate of 50 Hz giving a total of 6,00,000 sample point. Further details of the simulations can be found in [6].

Response data is processed using a popular OMA technique, Stochastic Subspace Iteration (SSI) [7, 8]. Only 60 channels of data are considered for this analysis as vertical accelerations in the tower and radial accelerations in the blade aligned vertically with the tower are not considered. Original time histories are downsampled by a factor of 10 so as to obtain a useful frequency range of 0-2.5 Hz. A total of 11 modes are identified in the frequency range of interest of 0-2 Hz. Estimated modal frequencies and damping values are shown in Table 1 which compare these values to the ones obtained from Eigenvalue solver of the simulation code.

Table 1: Mode Comparison

Mode number	Mode name	Eigenvalue Solver		OMA (SSI)	
		Freq (Hz)	Damp (%)	Freq (Hz)	Damp (%)
1	First lateral Tower Bending	0.273	1.45	0.271	0.75
2	First longitudinal Tower Bending	0.275	1.30	0.273	2.23
3	First drive train torsion	0.564	4.19	0.560	4.47
4	First yaw	0.604	0.61	0.606	5.40
5	First tilt	0.635	0.56	0.622	7.14
6	First symmetric flapwise bending	0.698	1.61	0.700	5.61
7	First edgewise vertical bending	0.951	0.56	0.950	0.66
8	First edgewise horizontal bending	0.975	0.52	0.972	0.38
9	Second yaw	1.526	0.73	1.526	2.73
10	Second tilt	1.655	0.52	1.652	3.07
11	Second symmetric flapwise bending	1.740	0.67	1.732	2.59

In Table 1, it is very interesting to note that, though modal frequencies obtained from Eigen value solver match well with those obtained from SSI, same isn't the case with damping estimates. However, this is on expected lines as Eigen value solver doesn't take into consideration aerodynamic forces. Modes involving out of rotor plane motion (Modes 2, 4, 5, 6, 9, 10, 11) are damped by the aerodynamic forces, even at standstill. This is due to the larger blade surface that interacts with surrounding air when the blades vibrate due to flapwise bending or tower longitudinal bending, thus, showing an increase in damping due to aerodynamic effects. Decrease of damping of other modes is also realistic due to negative aerodynamic damping of inplane vibrations when the flow around the blades is separated/stalled. This is seen in case of first lateral tower bending mode. The edgewise bending modes and drive train torsional mode are not much affected by the aerodynamic forces and hence the damping is comparable to structural damping obtained through theoretical calculations.

4. OMA Application on an Operational Turbine

While application of OMA on parked turbines is not such a complicated task, the same is not true in case of operational turbines. This is due to the fact that two of the key assumptions regarding OMA do not hold true for an operational turbine. In this section these issues are discussed and potential methodologies are suggested to overcome these issues.

4.1 Nature of Aerodynamic Forces

First issue that restricts applicability of OMA is the nature of aerodynamic forces exciting the turbine. As mentioned in section 2, OMA requires that the excitation forces are random broadband and uncorrelated in the frequency range of interest. The broadband aspect of excitation forces ensures that the measured responses on a structure due to these forces is not contaminated by the dynamics of the forcing and is formed primarily of only the dynamic characteristics of the structure. This is indeed what enables OMA algorithms to exploit the measured responses to obtain modal parameters of a structure. These assumptions are true when the turbine is in parked condition but rotation of the rotor (when turbine is in operation) changes the nature of the aerodynamic forces significantly and puts various constraints on applicability of OMA.

With regards to this issue, it is observed that the aerodynamic forces acting on an operational wind turbine are characterized by peaks at rotational frequency and its harmonics. These peaks are associated with thick tails which often masks the dynamics of the turbine in the frequencies in their neighbourhood. This is in violation of the assumption that the excitation forces are random and broadband. This nature of aerodynamic forces introduces significantly their own influence in the observed responses, often overwhelming the underlying structural properties, and hence makes the utilization of output responses, for modal parameter estimation procedure using OMA, a complicated task. This behaviour is explained in more details in [9]. Here, the results of those findings are summarized by means of Figures 1.a and 1.b.

In Figure 1.a, autospectra of aerodynamic force acting at the blade tip in edgewise direction is shown along with the response spectrum at that point. The force spectra is observed to have peaks at fundamental frequency of rotor rotation (1P) and also at subsequent harmonics (2P, 3P etc.). As mentioned earlier, these peaks are characterized with thick tails. It is evident from figure 1.a that these peaks along with their characteristic tails influence the response spectra, which is a combination of characteristics of both the force and the structure, significantly. The force is seen to dominate the response especially at the first three harmonics (1P, 2P and 3P) of rotor rotation, there by making it difficult to utilize the response for identifying dynamic characteristics of the structure. However, it is observed that influence of force dwindles at higher harmonics. Thus, it is possible to identify structural characteristics (as indicated in green in Figure 1.a) at higher frequencies and also in frequency zones that are not affected by characteristics of the force (for e.g. narrow frequency range between 1P and 2P).

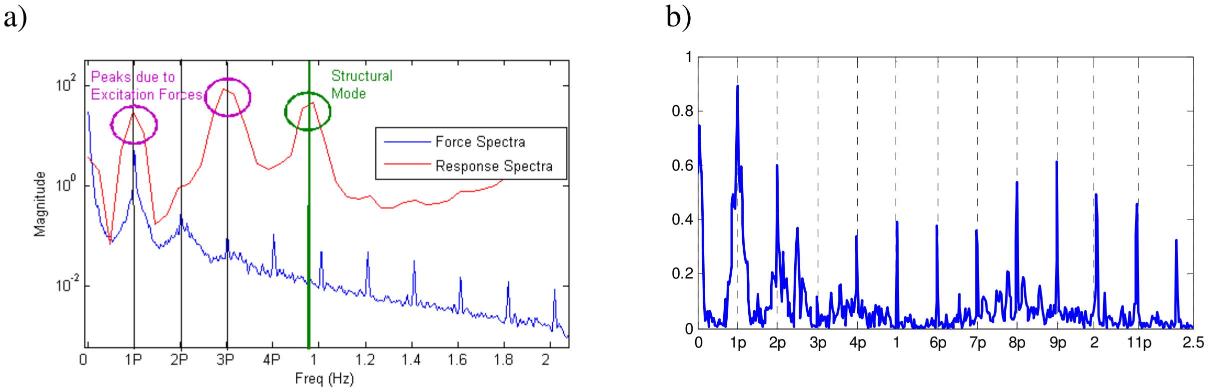

Figure 1: a) Power spectra of aerodynamic forces and observed response at blade tip in edgewise direction, b) Coherence (γ_{AB}) of the simulated aerodynamic forces at r = 26.4 m and r = 54.4 m on the same blade

It has been further observed that aerodynamic excitation forces acting at various points of the turbine blade are also correlated, thus violating the assumption of excitation forces being uncorrelated. This is demostrated by means of Coherence [10] plots in Figure 1.b, between excitation forces at two points, A and B, measured at radial distances of 26.4 m and 54.4 m on the same blade. This plot also signifies that since the coherence lowers down beyond the third harmonic, and also in frequency zones between the harmonics (like between 1P and 2P), it might be more likely to estimate the structural modes in these ranges in comparison to frequency regions having high coherence values.

In some sense, these observations show dependability of applicability of OMA to operational turbines on rotating speed of the turbine, as it's only around the fundamental harmonic and its multiples that OMA assumptions are violated. Thus, in context of these findings, it is suggested that a careful test planning is required to perform OMA. This means that OMA is performed only at those frequency ranges where aerodynamic forces are not overwhelming the measured response and OMA assumptions are still valid. For e.g. as per Figures 1.a and 1.b, in this particular case, OMA can be performed to extract the modes that are lying in the frequency ranges where coherence values are low and thick tails of force spectra are waning.

4.2 Time Varying Nature of Operational Wind Turbine

The second issue that presents an obstacle to application of OMA in case of an operational turbine is that the assumption of structure *time invariance* is violated. This assumption is distinctive to any kind of experimental modal analysis method and states that the object under test must not change during the test duration (or at least these changes should not be significant). However, this is not true in case of an operational wind turbine which consists of several substructures that move with respect to each other, resulting in violation of structural time invariance assumption. These phenomenons include yawing of nacelle about tower, rotation of the rotor, pitching of the blades etc.

In this context, various methods can be applied to deal with time varying nature of the structure. Since a turbine is not yawing or pitching frequently, time periods when these angles do not change (or change insignificantly) can be selected for the analysis. Further, a simple coordinate transformation can be performed in order to account for the changed yaw angle. Also averaged characteristic value of pitch angle can be used while accepting that the obtained modal parameters are "smeared" due to blades pitching during the test duration. However, rotation of rotor cannot be dealt with such methodologies and needs to be dealt with more advanced techniques. The effect of rotor rotation in mathematical terms is that of introducing a time varying term in the equations of motion of the turbine structure which results in modal parameters being dependent on time. Thus one way to analyze such a system is to come up with a methodology that is based on analysis of linear time varying systems. Though efforts have been initiated in this regard [11], the research is still in its infancy.

An alternative method to deal with this issue is to apply Coleman transformation or Multiblade Coordinate (MBC) transformation [12, 13]. MBC transformation converts the motion of individual blades described in rotating blade frame into the ground-fixed frame which results in elimination of the time periodic terms present in the equations of motion, thus making application of OMA possible. The idea behind MBC transformation is to replace individual blade deflections by some special variables which include information about all three blades and include information about instant azimuth angle ψ

$$a_{0,n} = \tfrac{1}{3}\sum_{i=1}^{3} q_{i,n};\; a_{1,n} = \tfrac{2}{3}\sum_{i=1}^{3} q_{i,n}\cos\psi_i;\; b_{1,n} = \tfrac{2}{3}\sum_{i=1}^{3} q_{i,n}\sin\psi_i \tag{7}$$

where $q_{i,n}$ is the n-th deflection of the i-th blade, a and b are multi-blade coordinates. The points with same n are located on the same radius on the different blades, and the deflection in the same direction (e.g. radial) is measured. Equations (7) represent forward transformation (i.e. blade coordinates to MB coordinates). The backward transformation is

$$q_{i,n} = a_{0,n} + a_{1,n}\cos\psi_i + b_{1,n}\sin\psi_i \tag{8}$$

Thus one can avoid time dependencies in the equation of motion and obtain meaningful modal parameters.

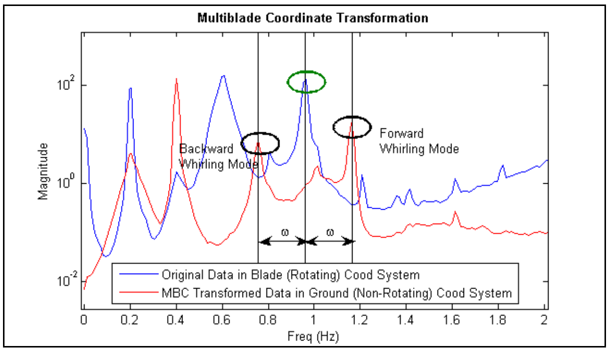

Figure 2: Effectivity of Multiblade Coordinate Transformation for identifying Whirling Modes.

The rotor related modes of the operational turbine are quite complex and hence difficult to identify. As observed while analyzing the parked turbine (refer Table 1), the asymmetric pair of modes, such as Out of plane 1st tilt and yaw modes and 1st in plane horizontal and vertical modes, have their natural frequencies close to each other. These pairs of asymmetric modes transform into a pair of whirling modes when the turbine starts rotating [14]. However, this whirling phenomenon is not inherently observable as typically the blade responses are measured in the blade (or rotating) coordinate system, where as whirling can only be observed in ground (fixed or non-rotating) coordinate system. MBC transformation enables the blade responses to be transformed into ground coordinate system, hence enabling observability and identification of the whirling modes.

The utility of MBC transformation in understanding the dynamics of the operating turbine can be illustrated by means of an example of the structural mode identified in previous section (Figure 1.a). Figure 2 shows the effect of MBC transformation on a blade response measured at the tip and in the edgewise direction. It is noteworthy, how MBC transformation enables the observation of whirling modes whose presence and nature cannot be identified while analyzing the data in blade (rotating) coordinate systems. The two whirling modes are separated by 2ω (ω is frequency of rotor rotation), which is in accordance with the theory. Dynamics of the turbine when it's operating, and the phenomenon of whirling modes, is explained in more details by means of analytical models in [14].

In light of the preceding discussion, it is interesting to underline the significance of this work that it provides a methodology to detect the presence of whirling modes through experimentally observed data while circumventing the issues related to time varying nature of the wind turbine structure. An example of successful utilization of this methodology can be found in [15].

5. Conclusions

This paper lays down the importance of dynamic characterization of wind turbines based on experimentation, especially in context of its relevance in variety of phases including, but not limited to, design, aeroelastic model validation, control systems etc. Since Operational Modal Analysis is a well known technique for dynamic characterization of complex structures, this paper assesses its applicability on wind turbines. It is shown that

OMA can be applied to parked turbines without encountering major problems. However, in case of operational turbines, it is shown that there are some challenges due to time varying nature of the wind turbine structure and the nature of aerodynamic forces exciting it. A methodology based on this knowledge and utilization of Multiblade Coordinate transformation is presented in this work. This approach enables the identification of whirling modes of the turbine, thus making it possible to characterize the dynamics of the operational wind turbine. The encouraging results obtained in this work, thus pave the way for evaluating the performance of this approach on an actual wind turbine in future.

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