Application of Operational Modal Analysis and Blind Source Separation / Independent Component Analysis Techniques to Wind Turbines

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Nomenclature

t	Time
ω	Frequency
$x(t)$	Vector of output observations
H	Frequency Response Function
F	Input Force
$[]^H$	Hermitian of a matrix
G_{XX}, G_{FF}	Response and Force Power Spectra
R_{pqk}, S_{pqk}	Mathematical Residue Terms
A	Mixing system or mixing matrix
$s(t)$	Source signals
Φ_r	Modal vector associated with r^{th} mode
η_r	Modal coordinates associated with r^{th} mode
Ψ	Modal filter matrix

Abstract

Wind turbines are complex structures and their dynamics vary significantly in operation, in comparison to that under stand still (parked) conditions. Presence of rotational loads and considerable aeroelastic effects makes it difficult to apply conventional system identification techniques to wind turbines.
Operational Modal Analysis (OMA) is a technique of determining dynamic characteristics of a structure based on the output responses only (Input excitation is assumed to be stochastic and its information is not required). Recently it was shown by means of analytical and experimental studies that Blind Source Separation and Independent Component Analysis (BSS/ICA) techniques, which are more common in bio-imaging, wireless communications etc, can also be utilized for system identification purposes in typical output only scenarios. This paper explores the possibility of applying these techniques (OMA and BSS/ICA) to wind turbines. These techniques lend themselves very well to this situation as wind turbine is a huge structure and also, stochastic excitation of turbine from the wind can be used as input. However, time variant nature of operating wind turbines and presence of harmonic components in excitation, still pose several challenge to application of OMA and BSS.
To tackle these issues one at a time, this paper focuses in understanding only the aeroelastic effects, thus avoiding effect of rotational loads (and hence presence of harmonic components in excitation force). Aeroelastic effects are significant even in case of parked wind turbines, thus studies are conducted on simulated data obtained for a parked turbine. Ability of OMA and BSS/ICA techniques in determining damping, which is a

combination of both structural and aeroelastic damping, is assessed by means of these studies. An OMA algorithm SSI-DATA (Data based Stochastic Subspace Identification) and a BSS technique called Second Order Blind Identification (SOBI) are used for this purpose. It is shown that these techniques work satisfactorily on parked turbine data, paving way to conduct further studies on more complex case of operational wind turbine.

1. Introduction

Utilization of only output response data for system identification purposes started way back in 1970s [1-4], however it was not till early 1990s that researchers started taking note of these techniques. During early 1990s, James et al. [5] proposed the NExT framework for utilizing output response time histories for modal parameter estimation purposes, thus laying foundation of Operational Modal Analysis. This research was a result of work performed at Wind Energy Research Organization at Sandia labs for testing wind turbines.

NExT involved a four stage process; data acquisition, calculation of correlation functions, use of traditional parameter estimation algorithms for finding system parameters and finally extraction of mode shapes. NExT was initially applied to a parked Vertical Axis Wind Turbine (VAWT). However, wind turbines behave very differently in operation, in which case aeroelastic effects are dominant and aeroelastic damping is significant in comparison to structural damping. Thus, NExT was subsequently applied to rotating VAWTs [5] Horizontal Axis Wind Turbine (HAWT) [6] and other structures like a rocket during launch [7]. It was noted in [5] that mode shape information is important to explain changes in damping with increase in turbine rotation rate and that better techniques are required for estimating low amplitude modes and removal of harmonic peaks. Surprisingly, though OMA subsequently got popular in various civil engineering applications (Bridges, buildings, stadiums etc) there wasn't much follow up with respect to wind turbines. One of the possible reasons for this could be that application of OMA to wind turbines is not a straight forward task due to the presence of considerable aeroelastic effects along with presence of rotational components.

In case of a parked wind turbine, all OMA assumptions and also those pertaining to Modal Analysis (System being linear, stationary and time invariant) are valid in general, except that aeroelastic effects are still considerable even in case of a parked wind turbine. The case of operational wind turbines is different though, as in addition to aeroelastic effects, rotational loads come into effect. Periodic nature of aerodynamic forcing, turbine system and the fact that system is now time-variant poses various challenges as these situations do not lend themselves naturally to OMA algorithms. However, possibility of estimating actual modal parameters which can aid in better understanding of dynamics of operating wind turbines are major incentives to be gained.

As mentioned earlier, aerodynamics plays an important role while designing wind turbines and it was during 1980s that the aeroelastic vibrations in wind turbines were first noticed. These problems were stall-induced edgewise blade vibrations, which later led to the development of a method for determining damping for edgewise blade modes [8]. This method utilized an exciter mechanism through which a particular mode is excited by means of a harmonic force and decaying response at the end of the excitation is used to estimate the damping.

In [11], the exciter mechanism method along with an Operational Modal Analysis algorithm, Stochastic Subspace Identification (SSI) [9, 10] were used for estimating aeroelastic damping of operational wind turbine modes. In this work, it was shown that blade pitch and generator torque variations can be used as exciter mechanisms for exciting particular modes of interest. However, this method suffers from limitations on account of the fact that excited turbine vibrations are not pure modal vibrations and therefore the estimated damping is not actual damping. Yet another limitation of this method was that it was not possible to achieve required pitch amplitudes to excite sufficiently modes other than the tower modes. SSI method performed better in comparison to the previous method, though longer time histories and averaging techniques were required. It was also able to estimate the closely spaced modes which caused problems for exciter method. Thus SSI showed promise in determining characteristics of an operational wind turbine.

This first use of SSI for OMA of wind turbines showed two limitations. First, the user was required to have some pre-knowledge of modal dynamics of the investigated turbine to be able to identify aeroelastic modes. Second, the aerodynamic excitation of rotor blades contain harmonics of integer multiples of the rotor speed due to the rotational sampling of the turbulence of wind, which are identified as modes in a standard SSI method.

The focus and motivation of this paper is to carry on these investigations further, to explore the possibility of using OMA techniques for estimating modal parameters, especially the effect of aerodynamic damping, including their variation with rotational speed, for an operational wind turbine. Additionally, use of an emerging technique called Blind Source Separation / Independent Component Analysis for this purpose is also illustrated in the paper.

As it was previously mentioned, the presence of periodic aeroelastic forces does not fit very well with the OMA assumptions; it is decided to tackle one problem at a time and hence current study focuses only on effect of aeroelastic damping in case of parked wind turbines and therefore, effects of periodic forces is avoided.

To avoid the uncertainties unavoidable for real measured data, the OMA and BSS methods are applied to simulated data generated by HAWC2 Wind Turbine simulator [35]. The simulated data are acceleration time histories generated for a number of points located on the tower and rotor blades. The output of OMA and BSS algorithms (namely, wind turbine modal parameters including aerodynamic damping) are compared with modal parameter obtained from the eigenvalue solver embedded into HAWC2 code. Since aerodynamic forces are excluded in the Eigen value solver of HAWC2, it only provides the structural modal parameters, and the aerodynamic damping is not accounted for. This makes invalid the direct comparison of modal parameters from the two experimental methods and the eigenvalue solver. However, from previous studies it is known, which and how the modes are affected by aerodynamic effects and this provides useful means of assessing the performance of OMA and BSS techniques to parked wind turbines.
Following section discusses the modal dynamics of wind turbines and theoretical background of OMA and BSS/ICA techniques. Section 3 includes details of simulated data and results of application of OMA and BSS/ICA studies conducted on this data. Conclusions and scope of future work are presented in section 4.

2. Theoretical Background

2.1 Modal Dynamics of Wind Turbines

The modal dynamics of wind turbines is governed by the flexibilities of the three main substructures: tower bending, drive train torsion, and blade bending (and torsion). All commercial MW-sized wind turbines have almost the same sequence of lower order modes at standstill (Refer Figure 1). The first two modes are the longitudinal and lateral (relative to the wind) tower bending modes, followed by the first drive train torsion mode and three rotor modes dominated by the first bending mode of the three blades, which is called the flapwise bending mode. The order of the drive train torsion mode relative to the rotor modes may differ from turbine to turbine, however, the mutual order of the rotor modes are the first yaw and tilt modes followed by the symmetrical flapwise rotor mode. Modes no. 7 and 8 are asymmetrical rotor modes that are dominated by the second bending mode of the blades, which is called the edgewise bending mode. The next modes are often the rotor modes dominated by the third blade bending mode, but for turbines with high towers they may be the second tower bending modes.

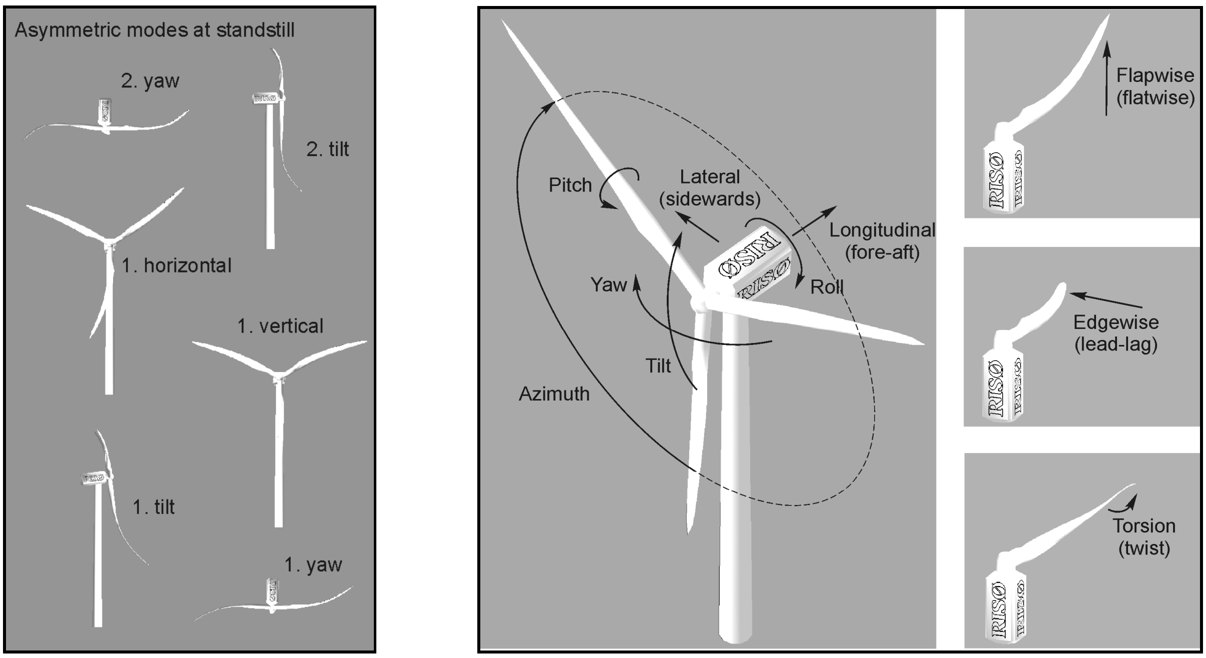

Figure 1: Modes of a Standstill Wind Turbine

The frequencies of tower bending modes, drive train torsion modes, and symmetrical rotor modes are almost independent of rotor speed (except for centrifugal stiffening effects on the blade bending modes). The asymmetrical rotor modes couple in pairs of forward and backward whirling modes for each blade bending (or torsion) modes. If a pair of whirling modes belonging to a blade mode is *pure*, then their modal frequencies in the

inertial frame will be given by the particular blade mode frequency plus and minus the rotor speed (see [12] for more details on modal dynamics of turbines).
The damping ratios of all turbine involving out of rotor plane velocities or rotation of the blades about their length-axis (the pitch axis) will be highly affected by the aerodynamic damping due to the direct aeroelastic coupling from angles of attack and thereby the aerodynamic forces along the blades. The first longitudinal tower bending mode is therefore highly damped with common damping ratios around 20% for pitch-regulated turbines. However, for stall-regulated turbines this aeroelastic tower damping depends on the stall characteristics of its blade airfoils which in some cases can lead to negative aerodynamic damping of tower bending modes. Rotor modes involving flapwise blade bending modes are also highly damped with common damping ratios above 20% for pitch-regulated turbines, but may also be low or negatively damped as the tower modes for stall-regulated turbines. The total aeroelastic damping of the first lateral tower bending mode and the rotor modes involving edgewise blade bending modes are much less affected by the aerodynamic damping because the blade motion occur mostly in the rotor plane. Their damping ratios therefore do not depend highly on the operational conditions of the turbine (wind speed, blade pitch setting, and rotor speed); however these modes are low damped, and in some cases of stall-regulated turbines even slightly negatively damped by the aeroelastic interaction of aerodynamic forces and turbine motion.

2.2 Operational Modal Analysis (OMA) and Blind Source Separation / Independent Component Analysis (BSS/ICA) Techniques

This section describes briefly main theoretical concepts and important assumptions behind Operational Modal Analysis and utilization of BSS/ICA for OMA purposes. For more detailed understanding of OMA and associated algorithms one can refer [13].

Operational Modal Analysis

As stated in previous section, OMA is a system identification technique based only on measured output responses. OMA does not require input force information but it makes certain assumptions about the nature of the input excitation forces. These include, 1) Power spectrum of the input force is assumed to be broadband and smooth. This means that the input power spectra is constant and has no poles or zeroes in the frequency range of interest. 2) Input forcing is further assumed to be uniformly distributed spatially. Both these assumptions imply that excitation is considered stochastic in time and space.
Mathematically, if *{X(ω)}* is the measured response and *{F(ω)}* is the input force, the relationship between them in terms of frequency response function (FRF) *[H(ω)]* is given as follows [14]:

$$\{X(\omega)\} = [H(\omega)]\{F(\omega)\} \tag{01}$$

$$\{X(\omega)\}^H = \{F(\omega)\}^H [H(\omega)]^H \tag{02}$$

Now multiplying Eq. (14) and Eq. (15)

$$\{X(\omega)\}\{X(\omega)\}^H = [H(\omega)]\{F(\omega)\}\{F(\omega)\}^H [H(\omega)]^H \tag{03}$$

or with averaging,

$$[G_{XX}(\omega)] = [H(\omega)] \; [G_{FF}(\omega)] \; [H(\omega)]^H \tag{04}$$

where $[G_{XX}(\omega)]$ is the output response power spectra and $[G_{FF}(\omega)]$ is the input force power spectra.
Going back to the assumption that input force spectrum is constant, it is easy to note that output response power spectra $[G_{XX}(\omega)]$ is proportional to the product $[H(\omega)][H(\omega)]^H$ and order of output response power spectrum is twice that of frequency response functions. Since $[G_{FF}(\omega)]$ is constant, $[G_{XX}(\omega)]$ can be expressed in terms of frequency response functions as

$$[G_{XX}(\omega)] \propto [H(\omega)][I][H(\omega)]^H \tag{05}$$

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

$$G_{pq}(\omega) = \sum_{k=1}^{N} \frac{R_{pqk}}{j\omega - \lambda_k} + \frac{R^*_{pqk}}{j\omega - \lambda^*_k} + \frac{S_{pqk}}{j\omega - (-\lambda_k)} + \frac{S^*_{pqk}}{j\omega - (-\lambda^*_k)} \tag{06}$$

which indicates that power spectrum data not only contains information about positive poles (λ_k) of the system but also negative poles ($-\lambda_k$), or in other words, the same information twice. R_{pqk} and S_{pqk} are k^{th} mathematical residue terms and are not to be confused with residue terms obtained using FRF based model as these term do not contain modal scaling information (since input force is not measured). It is important to note that this equation shows that power spectra contains all information needed to define the dynamic characteristics of a system (except for modal scaling factor), provided the OMA assumptions are true.

Blind Source Separation (BSS) or Independent Component Analysis (ICA)

BSS/ICA can be seen as an extension to Principal Component Analysis (PCA) which aims at recovering the source signals from a set of observed instantaneous linear mixtures without any *a priori* knowledge of the mixing system.
Mathematically, ICA problem can be formulated as

$$x(t) = A\, s(t) \tag{07}$$

where $x(t)$ is a column vector of m output observations representing an instantaneous linear mixture of source signals $s(t)$ which is a column vector of n sources at time instant t. A is an m X n matrix referred to as “mixing system” or more commonly as “mixing matrix”. A detailed discussion of the subject of BSS/ICA can be found in [15-21] which provides general introduction and details of various aspects of BSS/ICA.
BSS techniques aim at recovering both the source signals $s(t)$ and system mixing matrix A and in that sense they bear basic similarity with OMA. In recent times there have been attempts at utilizing these techniques for OMA purposes [22-27]. These papers, illustrate the use of BSS/ICA techniques to analytical and experimental data. BSS/ICA techniques are less time consuming and avoid the need of traditional stability/consistency diagram which are sometimes difficult to interpret.
From theoretical point of view, link between BSS/ICA and modal analysis can be established through the concept of expansion theorem [28] and modal filters [29-31]. According to the expansion theorem response of a distributed parameter structure can be expressed as

$$x(t) = \sum_{r=1}^{\infty} \phi_r \eta_r(t) \tag{08}$$

where Φ_r are the modal vectors weighted by the modal coordinates η_r. For real systems, however, response of the system can be represented as a finite sum of modal vectors weighted by the modal coordinates. To obtain a particular modal coordinate η_i from response vector x, a modal filter vector ψ_i is required such that

$$\psi_i^T \phi_i = 0, \qquad for \quad i \neq j \tag{09}$$

and

$$\psi_i^T \phi_i \neq 0, \qquad for \quad i = j \tag{10}$$

so that

$$\psi_i^T x(t) = \psi_i^T \sum_{r=1}^{N} \phi_r \eta_r(t) \tag{11}$$

or

$$= \psi_i^T \phi_i \eta_i \tag{12}$$

Thus modal filter performs a coordinate transformation from physical to modal coordinates. Multiplying the system response x with modal filter matrix Ψ^T results in uncoupling of the system response into single degree of freedom (SDOF) modal coordinate responses η.
In order for ψ_i to exist, the associated modal vector Φ_i must be linearly independent with respect to all other modal vectors [29]. This is also the reason why ICA / BSS based techniques can be utilized for the purpose of decomposing the output system response into a product of modal vectors and corresponding modal coordinate responses. A modal filter vector is unique if and only if the number of sensors used for the modal filter

implementation is equal to the number of linearly independent modal vectors contributing to the system response. In this work, *Second Order Blind Identification* (SOBI) algorithm is used for OMA purposes. SOBI algorithm utilizes joint diagonalization procedure [15, 32, 33] to estimate an orthogonal matrix that diagonalizes a set of covariance matrices [25]. One important aspect of BSS/ICA algorithms, in relation with OMA, is that one can at most extract as many modes as number of sensors used to collect the output response.

3. Simulations on a Virtual Turbine: Results and Discussions

The virtual turbine used in present analysis is the 5MW machine designed by Jonkman [34] as a numerical reference turbine. The modeling and simulations are performed using the nonlinear aeroelastic multi-body code called HAWC2 [35].

Simulation is done for a standstill case, where the blades are at fine pitch and the drive train is locked by an assumed mechanical brake on the generator side of the gearbox. The wind speed is 18 m/s in hub height with a logarithmic wind shear. Stochastic forcing of the turbine is achieved by simulated atmospheric turbulence with a low intensity of 5% obtained using Mann's turbulence model of correlated turbulence with a Kaimal spectrum. The length of turbulence box is 217.8 km (18 m/s times 12100 s, where first 100 s are reserved for unsaved transients leaving a time series of 12000 s), and there are 16384 sheets of 32 by 32 points. The longitudinal resolution of turbulence box is therefore 13.29 m, which is significantly longer than in turbulence boxes used for normal 10 min simulations for aeroelastic turbine analysis. The coarse resolution leads to artificial excitation at the updating frequency of 1.354 Hz (18 m/s divided by 13.29 m), which must be neglected in the following analysis.

Response time histories in terms of accelerations are recorded 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.

3.1 Operational Modal Analysis

Simulated data is processed using Stochastic Subspace Identification (SSI) algorithm. Vertical accelerations for the tower and radial accelerations for one of the blade aligned with the tower (Blade 1 in Figure 2), are neglected for this analysis. Thus only 60 channels of response data are analyzed. The measurement directions at various locations on the turbine are indicated in Figure 2. Original time histories are downsampled by a factor of 10 so as to obtain a useful frequency range of 0-2.5 Hz. Additionally, projection channels are used to enhance the performance of the algorithm [36].

Figure 3 shows the stabilization diagram obtained using SSI. Note that in the stabilization diagram only stable modes are indicated.

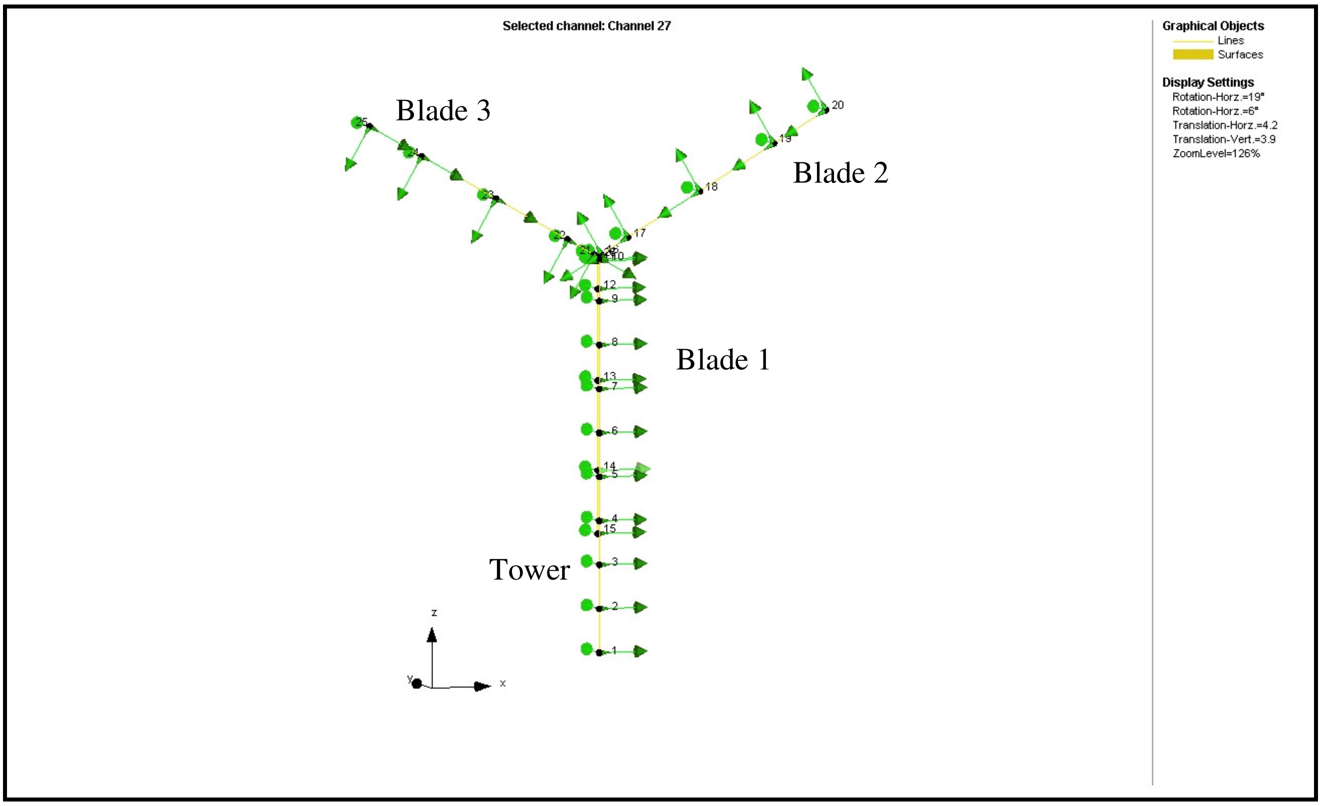

Figure 2: Measurement Locations and Degrees of Freedom

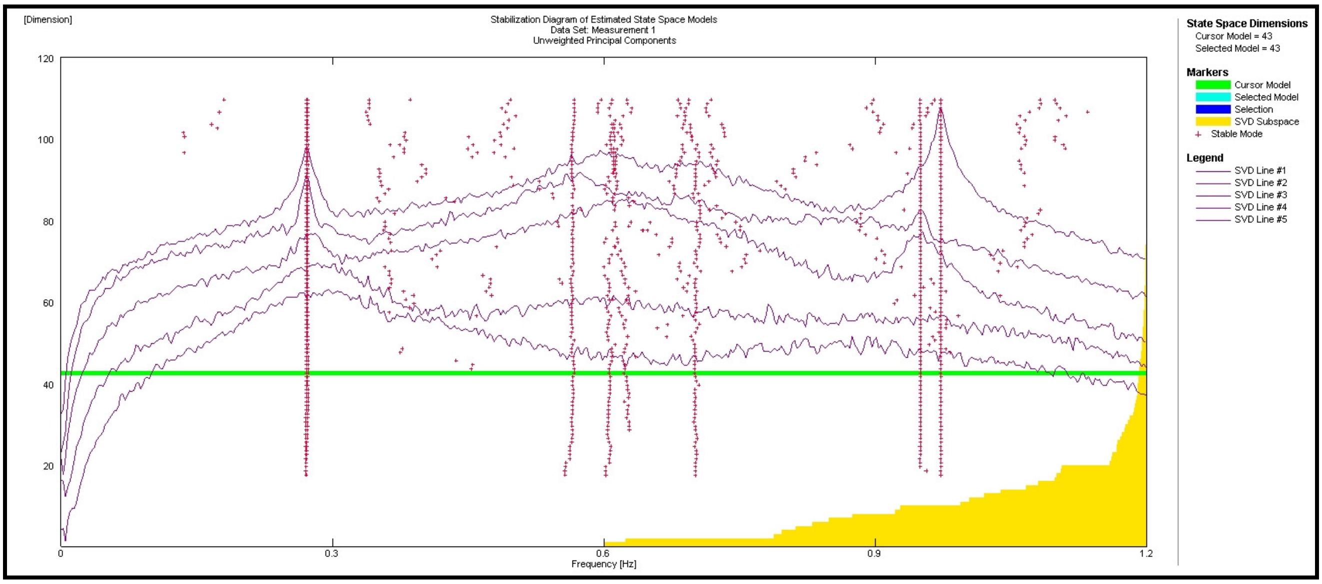

Figure 3: Stabilization Diagram for SSI Algorithm

SSI is able to find all eight modes in the frequency range of 0-1 Hz. However, the stability with regards to modes at 0.60 and 0.62 Hz is not as good as other modes. A total of 11 modes are obtained between 0-2 Hz frequency range as listed in Table 1.

3.2 Blind Source Separation / Independent Component Analysis

In case of BSS/ICA the simulated response is downsampled by a factor of 5 to get a useful frequency range of 0-5 Hz. In this case as well, the same 60 channels are used for analysis as in case of OMA. Figure 4 show the plot of auto-power spectra of modal coordinate responses η, obtained using SOBI algorithm and modal frequencies and damping values are listed in Table 1. As stated in section 2, SOBI decouples the system response to corresponding SDOF modal coordinate responses. Here the algorithm is set to identify 36 modes in frequency range of 0-5 Hz. It is anticipated that the first 8 modes, which are the focus of this study, will be obtainable amongst the 36 modes identified by SOBI. It is important to note that, from algorithmic point of view, one can estimate at most 60 modes from this dataset, as the total number of sensors considered is 60. Obviously, not all the modal coordinate responses resulting from SOBI correspond to actual modes. It can be clearly seen from Figure 4 that in some cases the resultant modal coordinate response is not due to an underlying SDOF system (or that the output response has not been decoupled into SDOF modal coordinate responses). However, all the modes in frequency range of interest are well identified. The process of finding out modal frequency and damping corresponding to each mode involves calculating correlation functions for modal coordinate responses representing the underlying SDOF system and using zero crossing and logarithmic decrement method for estimating frequency and damping.

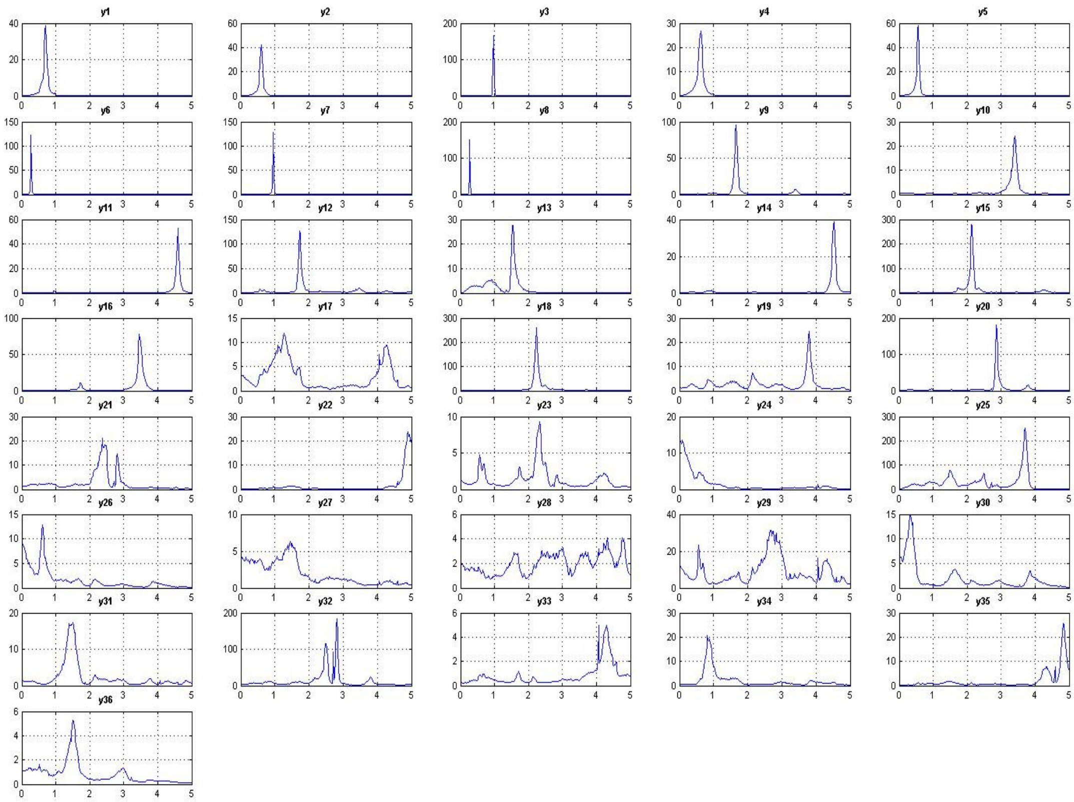

Figure 4: Auto-power Spectra of SOBI Modal Coordinate Responses

3.3 Result Comparison and Discussion

Table 1 shows the comparison of OMA and BSS/ICA results with modes obtained from Eigen value solver. It also includes three modes between 1-2 Hz frequency range, in order to further compare the performance of SSI and SOBI. It is very interesting to note that, though modal frequencies obtained from Eigen value solver match well with those obtained from SSI and SOBI, 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. The second yaw mode at 1.53 Hz (Plot 3,3 in Figure 4) is not very well identified i.e. the modal coordinate response is not entirely due to this mode. This results in inconsistent damping estimate and hence it is not included in compiled results (Table 1). The Cross MAC plot in Figure 5 indicates that mode shapes from SSI and SOBI match well for most modes, although not for all the modes (Drive train torsional and edgewise bending modes).

Table 1: Mode Comparison

Mode number	Mode name	Eigen value Solver		OMA (SSI)		BSS/ICA (SOBI)	
		Freq	Damp	Freq	Damp	Freq	Damp
1	First lateral Tower Bending	0.273	1.45	0.271	0.75	0.273	0.78
2	First longitudinal Tower Bending	0.275	1.30	0.273	2.23	0.273	2.22
3	First drive train torsion	0.564	4.19	0.56	4.47	0.56	5.15
4	First yaw	0.604	0.61	0.606	5.40	0.605	5.55
5	First tilt	0.635	0.56	0.622	7.14	0.63	8.41
6	First symmetric flapwise bending	0.698	1.61	0.7	5.61	0.695	5.73
7	First edgewise vertical bending	0.951	0.56	0.95	0.66	0.954	0.87
8	First edgewise horizontal bending	0.975	0.52	0.972	0.38	0.975	0.47
9	Second yaw	1.526	0.73	1.526	2.73	1.535	-
10	Second tilt	1.655	0.52	1.652	3.07	1.655	2.85
11	Second symmetric flapwise bending	1.74	0.67	1.732	2.59	1.735	3.47

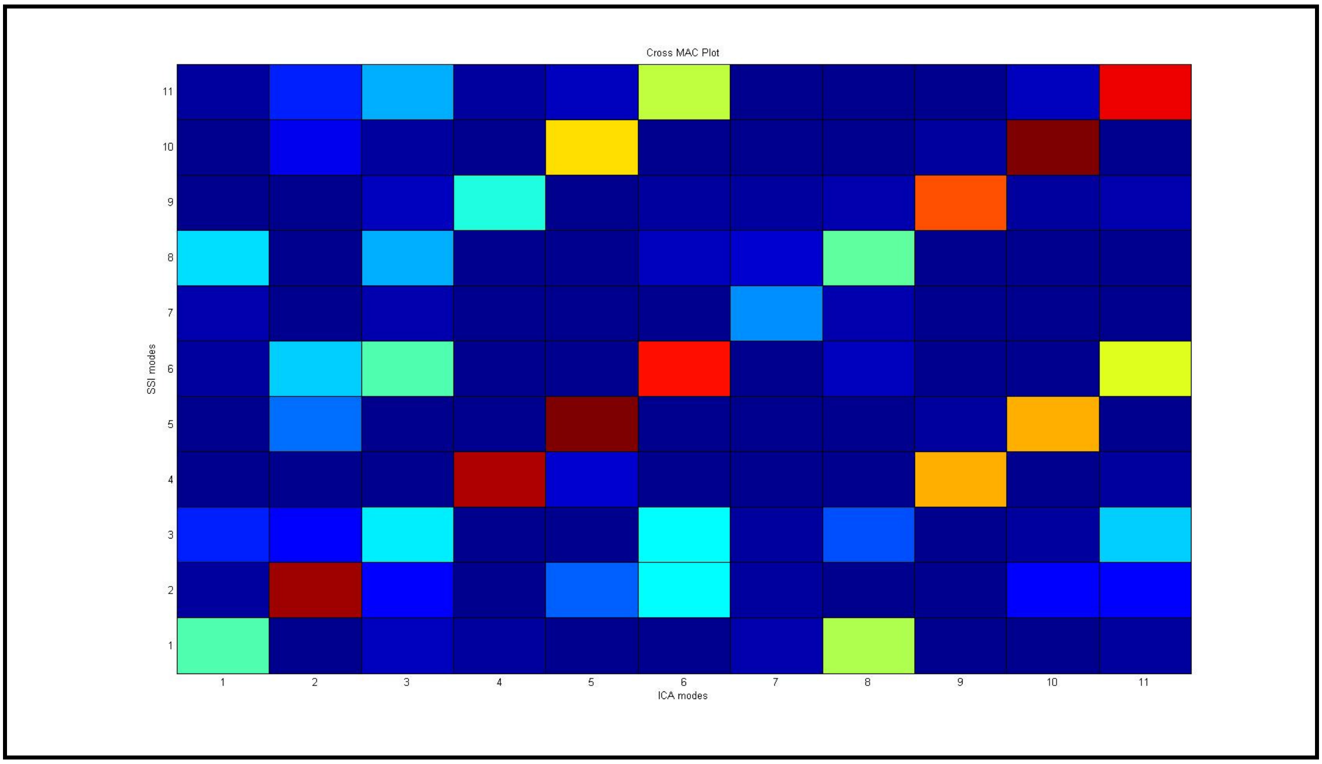

Figure 5: Cross-MAC between SSI and SOBI modes

4. Conclusions and Scope of Future Work

Main motivation for conducting these studies was to assess performance of OMA and BSS/ICA techniques when applied to wind turbines. Since wind turbines are complex structures, it was decided to focus on one issue at a time and thus studies were conducted on parked turbines. In case of a parked turbine, the rotational forces don't come into play, although aeroelastic effects are still significant.

An OMA algorithm, SSI-DATA and a BSS technique, SOBI, are applied to simulated data obtained for a parked wind turbine. Results show that both techniques perform satisfactorily. It is noticed that damping values obtained using two techniques are quite similar, but they differ considerably from the damping values obtained from Eigen value solver. This is due to the fact that damping obtained from SSI-DATA and SOBI are a combination of structural and aeroelastic damping where as Eigen value solver provides only structural damping. Where as aeroelastictity results in increasing damping of certain modes and decreasing damping of others, depending on how the surface interacts with surrounding air; there are some modes like edgewise bending and drive train torsional modes in whose case damping is not affected as aeroelastic effects are not significant. These results are on expected lines and hence very encouraging.

As mentioned before, the real challenge in case of wind turbines lies in establishing their dynamic characteristics while in operation when the system becomes time variant and rotational loads come into play along with the aeroelastic effects. Based on the encouraging results of this work, the future course of action involves carrying out studies on simulated data for operating wind turbines. Depending on the success of studies conducted on simulated dataset, these studies will be substantiated with studies on data obtained from real operational wind turbine.

From a broader perspective, benefits to be gained out of this study are in terms of better understanding of dynamics of operational wind turbine and making tools like OMA suitable and robust for application to wind turbines.

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