

Operational Modal Analysis of a Wind Turbine Wing Using Acoustical Excitation

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Key Words: Operational Modal Analysis, Acoustical Excitation

ABSTRACT

Operational Modal Analysis also known as Ambient Modal Analysis has an increasing interest in mechanical engineering. Especially on big structures where the excitation and not less important the determination of the forces is most often a problem.

In a structure like a wind turbine wing where the modes occur both close in frequency and bi-directional the ambient excitation has big advantages. In this paper modal parameters are identified from the wing by operational modal analysis. For the parameter identification both parametric and non-parametric techniques are used. Advantages and disadvantages are discussed and results from the different techniques are compared

Symbols	
Δt	Sampling time step
y_i	Response vector
f	Natural frequency
ζ	Damping ratio
Φ, Ψ	Mode shape matrices
$MAC(i, j)$	MAC matrix

this two-dimensional model the results from the two recordings are linked together. The wing is considered as stiff in the length direction so vibrations in this direction are disregarded.

1. Introduction

Operational Modal Analysis also called *Ambient Modal* or *Output only Modal* is a technique for modal parameter estimation without knowing the input loading force. The method has over a decade been used for parameter estimation on civil structures such as bridges and towers where artificial excitation and determination of forces exhibits a problem.

In this paper the use of the Operational Modal Analysis method for a 1:5 scale wind turbine wing is described. The object is a detailed model of one of the blades from a 675 kW wind turbine. The wing has been made for lab investigations of static as well as dynamic parameters. *Figure 1.* shows a picture of the set-up used for the measurements. The wing itself is supported by a console which is regarded as stiff compared to the wing itself.

24 accelerometers are mounted in two rows along the wing. Two time recordings were taken, one with the accelerometers perpendicular to the surface (Z-direction) and one pointing in the direction of rotation (X-direction). To determine the combined modes in

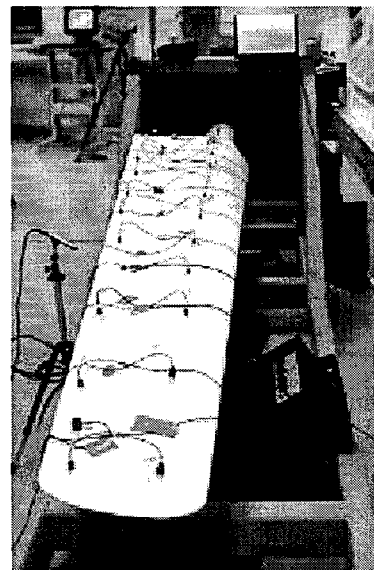


Fig. 1 Wind Turbine Wing with acoustic excitation. Loudspeaker in the background

The aim of the measurements is to determine the lower modes for flutter investigations. Also modes in the audible frequency range typical 30-400 Hz are of interest due to potential noise problems.

The wing was exposed to an acoustic load by means of a loudspeaker placed beneath the wing. Although the aim is to use Operational Modal Analysis for the test the sound level was measured and analysed as well. *Figure 1.* shows a microphone placed in front of the wing. This measurement was done to ensure presence of energy in the frequency range of interest. The spectral distribution does not need to be flat.

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To compare the results with classical input/output based modal analysis, mobility measurements using hammer excitation with subsequent curve fitting in ME' scope was performed.

2. Data Processing Equipment

The response data are acquired using the Brüel & Kjær PULSE multi analyser platform that also provides FFT based validation tools prior to the processing in the Operational Modal Analysis software (Ref [9]).

The Brüel & Kjær/SVS Operational Modal Analysis software takes the raw time data and based hereupon estimates the modal parameters.

The program uses two different techniques: a non-parametric technique based on Frequency Domain Decomposition (FDD), and a parametric technique working on the raw data in time domain, a data driven Stochastic Subspace Identification (SSI) algorithm.

The results from the different techniques can be compared using the programs validation tools.

3. Background

Operational Modal Analysis is a technique where modal parameters are estimated from the response data without known input forces.

Classical mobility based modal analysis uses techniques, which relates a known response to a known force using estimators such as H_1 , H_2 etc. Such estimators carry information of the system under test and are independent of the input loading and even work in cases of noise in input or output signal.

As the force is unknown some assumptions has to be made. If the structure were excited by white noise the response would carry the information of the system under test. But in practice excitation by white noise is not a possibility and the model must take the (unknown) excitation source into account. In Operational Modal Analysis we have to work with the so-called *combined model*, consisting of the following parts:

- **The system under test** (our final result)
- Frequency dependant random noise from the excitation
- Computational noise
- Measurement noise
- Harmonics from rotating parts

The purpose of the Operational Modal Analysis estimators is first to fit the combined model to the experimental data containing all these components and hereafter to extract the system parameters leaving the undesired components behind.

Operational Modal Analysis has included a range of estimators divided in two main groups: Frequency Domain Decomposition and Stochastic Subspace Identification.

$$G_{yy}(j\omega) = \sum_{k=1}^N \frac{d_k \phi_k \phi_k^T}{j\omega - \lambda_k} + \frac{\bar{d}_k \bar{\phi}_k \bar{\phi}_k^T}{j\omega - \bar{\lambda}_k} \quad (1)$$

The **Frequency Domain Decomposition (FDD)** technique used for the Operational Modal Analysis is an extension of the classical frequency domain approach. The classical approach is based on signal processing using the Fourier Transform and the modal transformation. The modal transformation in its output only formulation is seen in (1). The modal information is extracted by singular value decomposition for each frequency line in the FFT. The information of the number of modes is held in the number of singular values, and the mode shape in the singular vectors. Ref. [1] and ref. [8]

Stochastic Subspace Identification (SSI) is on the contrary to the FDD technique a class of techniques that uses time domain technique. SSI is formulated and solved using state space formulations of the form

$$\begin{aligned} x_{t+1} &= Ax_t + w_t \\ y_t &= Cx_t + v_t \end{aligned}$$

where x_t is the Kalman sequence that in SSI is found by a so-called orthogonal projection technique, Overschee and De Moor [3].

It can be shown [2] that by performing a modal decomposition of the A matrix and introducing a new state vector the equation becomes:

$$\begin{aligned} z_{t+1} &= [\mu_i] z_t + \Psi \varepsilon_t \\ y_t &= \Phi z_t + \varepsilon_t \end{aligned}$$

where $[\mu_i]$ is a diagonal matrix holding the discrete poles, and where the matrix Φ is holding the left hand mode shapes (physical mode shapes) and the matrix Ψ is holding the right hand mode shapes (non-physical mode shapes).

The right hand mode shapes are also referred to as the initial modal amplitudes, Juang [4].

The specific technique used in this investigation is the Principal Component algorithm; see Overschee and De Moor [3].

4. Results

4.1 Mobility measurements

Mobility measurements are performed using impact hammer excitation. Random impact is used since the frequency span of 200Hz with 800 FFT lines gives a record length of 4s.

The structure is excited in one of the "free-end" corner points with a direction approximately 45degrees angle to both the X- and the Z-axis in order to ensure excitation of all the modes. The response is measured in the X- and Z-direction of the 24 points.

Figure 2. shows one of the Frequency Response Functions (Acceleration) and the corresponding

coherence function.

The Frequency Response Functions are curve fitted and the modal parameters extracted for comparison with the modal model extracted using operational modal analysis.

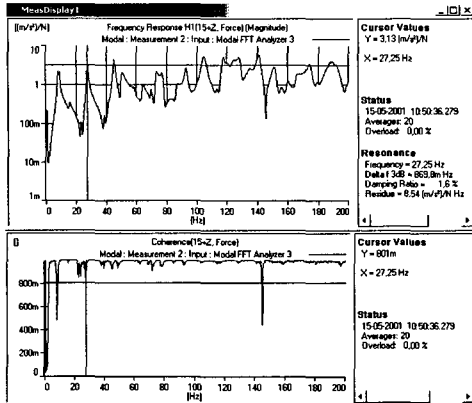


Fig. 2 Example of a Frequency Response Functions (Acceleration) and corresponding coherence function.

4.2 Operational Modal

Acoustic excitation from a loudspeaker, situated below the structure, is used for the operational modal analysis. The acoustic signal is a low frequency random signal. 60s of time samples in a frequency span up to 200Hz are captured. Measurements are made in 24 points in X- and Z-direction. This is done in two sessions (data sets) by first measuring the Z-direction and then the X-direction. A biaxial accelerometer mounted close to one of the “free-end” corner points provides the reference signals used to link the results from the two data sets together.

Both the FDD and the SSI methods are used for extraction of the modal parameters. A number of peaks appear very clearly in the FDD, specially in the low frequency range below 100Hz as seen in Figure 3.

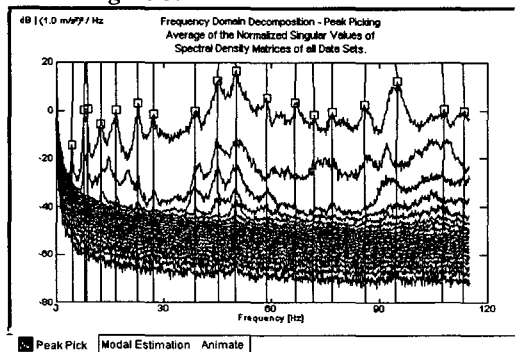


Fig. 3 Frequency domain decomposition in terms of average of normalized singular values of spectral density matrices of all data sets

These peaks are expected to be caused by structural resonances and not by response due to a high-level

force excitation in a narrow-band. 17 modes are detected below 110Hz; see Figure 3. The frequency and damping values are determined using a SDOF model applied in a user-definable frequency band around the peak.

For the SSI methods a number of analyses are performed. A maximum state space dimension of 200, corresponding to a maximum of 100 modes, is applied in a frequency span up to 200Hz.

For the Canonical Variate Analysis (CVA) algorithm models with a state space dimension of around 140 seems to give models which agree with the measured data for frequencies down to approximately 40Hz. This is verified by looking at the stabilization diagram and by synthesizing the response auto- and cross-spectra from the model and comparing this with the measured spectra. Higher model order does not give much better agreement.

Figure 4 shows a stabilization diagram for the CVA algorithm. A mode whose modal parameters, frequency damping and MAC, change within user-definable intervals compared to the previous lower model order is called a stable mode and is indicated by a red +. If one of the parameters change more than defined by these intervals the mode is defined as unstable and is indicated by a green x. Modes with damping values outside a user-definable range, e.g. more than 5% or negative, are called noise modes and are indicated by a yellow x.

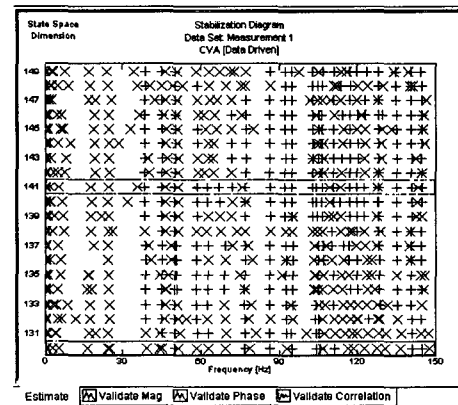


Fig. 4 Stabilization diagram for the CVA algorithm. + (red), x (green) and x (yellow) indicate stable, unstable and noise modes respectively.

Figure 5. shows a comparison of the synthesized response autospectrum, for a selected state space dimension of 141, with the measured response autospectrum. Good agreement is found in the frequency range from 40Hz to 200Hz, with the exception of the two modes around 150Hz. In the low frequency range below 40Hz, however, the model is not very good and use of higher state space dimensions

does not improve it very much. Therefore low-pass filtering and decimation to 50Hz is performed on the time data and new SSI analyses are performed. Figure 6. shows a comparison between a synthesized autospectrum, using a state space dimension of 123 from the new SSI analysis, and the measured autospectrum.

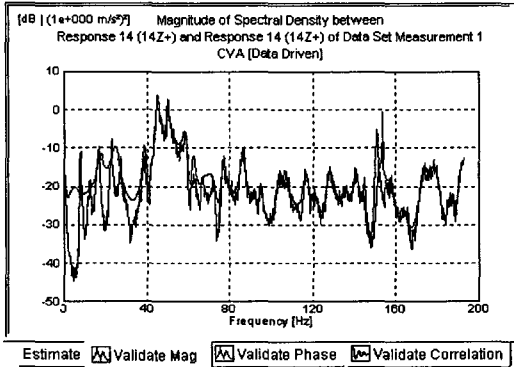


Fig. 5 Example of comparison of a synthesized response autospectrum with the measurement. Frequency span of 200Hz and selected state space dimension of 141

Very good agreement is now found down to approx. 10Hz. The low frequency modes, including those below 10Hz, are very well estimated from the FDD method and further low-pass filtering and decimation for the SSI methods was not performed.

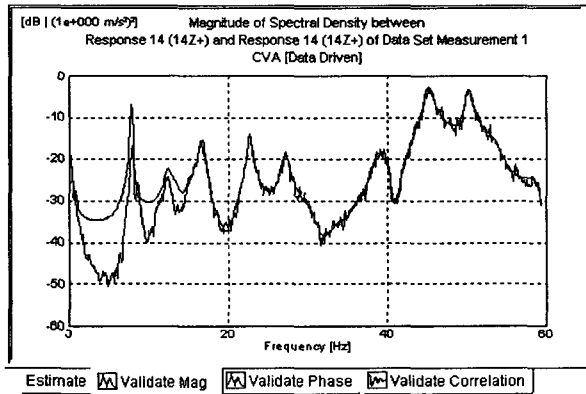


Fig. 6 Example of comparison between a synthesized autospectrum and the measured autospectrum. A CVA model on the 50 Hz low-pass filtered and decimated signals with a state space dimension of 123 is used.

The frequencies of the estimated modes up to 110Hz from the different methods are compared in Table 1. The FDD method provides very good estimation of the modes especially in lower frequency range and it is the only method, which finds the mode at 4,4Hz. There is good agreement with the modes estimated (curve fitted) from the mobility measurements.

The CVA method, by combining the results from the two frequency spans, also provides good agreement with the modes estimated from the mobility measurements. The different mode shapes are compared by overlay of the animated wire frames and by calculation of the cross-MAC functions. As examples the estimated shapes of the modes at 22Hz, 45Hz and 85Hz from the mobility measurement and the CVA method are compared in Figure 7. Good agreement is seen and the cross-MAC are calculated to be 0.78, 0.95 and 0.82 respectively.

	a) Modes from mobility test:	b) OMA FDD Enh:	c) OMA CVA 200Hz:	d) OMA CVA 50HzDec:
Mode	Freq. Hz	Freq. Hz	Freq. Hz	Freq. Hz
1		4,41		
2	8,16	7,83		7,79
3	8,84	8,55		
4		12,5		12,2
5	15,4	16,6		16,9
6	22,9	22,7		22,7
7	27,3	27,1		27,1
8	38,6	39,1	39,0	38,6
9				39,6
10	45,0	45,4	45,3	45,1
11	50,1	50,2	50,1	
12	59,0	58,6	58,6	
13	63,6		62,5	
14	69,2	66,8	66,3	
15	72,9	71,7		
16	77,2	77,0	76,9	
17	86,1	86,2	86,5	
18	92,8			
19	96,4	94,5	94,5	
20	104		104	
21	107	107,2	106	

Table 1. Comparison of the modal frequencies estimated from:

- a) Curve fitting on mobility functions (“classical” modal analysis)
- b) FDD method
- c) CVA method in frequency span of 200Hz
- d) CVA method in frequency span of 50Hz

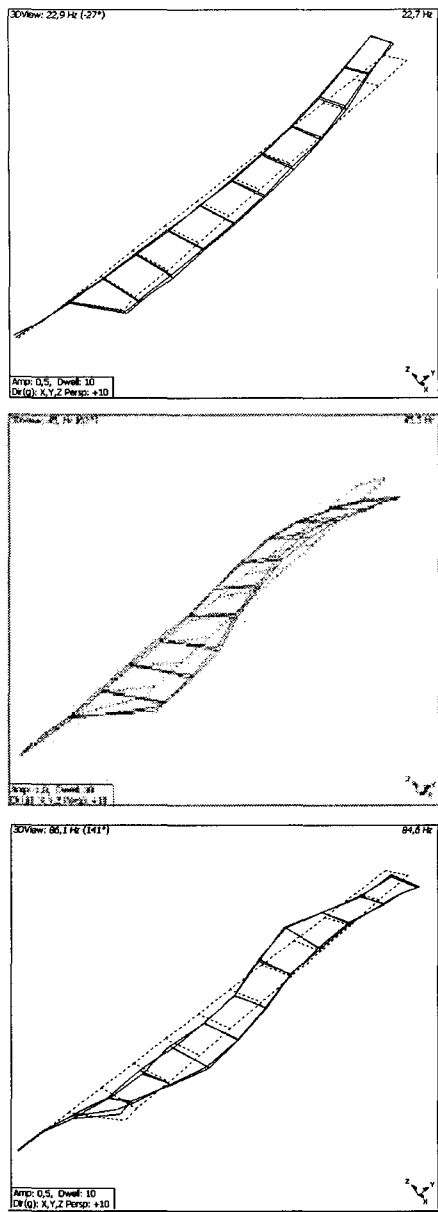


Fig. 7 Comparison of the estimated shapes for the modes at 22Hz, 45Hz and 85Hz from the mobility measurement and the CVA method.

5. Conclusion

5.1 Results

The Operational Modal Analysis shows to be an efficient tool for the determination of modal parameters when the input loading force for some reason is unknown or impossible to measure.

When we compare the results from the mobility test with those from the FDD method there is a good correlation even at higher frequencies where the peaks are smeared out and the modes are relatively close.

The time domain methods require long time records depending of the lowest frequency of interest. The length of the time record required for the Stochastic Subspace Identification technique depends upon the time period of the lowest modal frequency of interest. The factor between this period time and the required record length depends upon the number of modes and modal coupling.

Comparing the results form the mobility test with the Stochastic Subspace Identification technique implemented by the CVA technique it is seen that the correlation is good at modes above 39 Hz; column c), Table 1.

The direct way to get the modes at the lower frequencies as well would according to the theory be to make longer time recordings, use higher state space dimensions and thereby extending both the measurement- and the calculation time.

Instead a low-pass filtering and decimation process on the same data is performed and the modes at the lower frequencies are identified as seen in column d) in Table 1. The estimated lower mode shows good correlation with those estimated from the mobility test.

5.2 General

In this paper Operational Modal Analysis has been showed as an efficient tool for determining the modal parameters on a wing of a wind turbine during simulated operational conditions.

Previously such tests have been done using torsion shakers inserted into the drive shaft of the turbine, which is a both time consuming, expensive, and to some extent risky method. The Operational Modal Analysis technique opens new possibilities for determination of the modal parameters from response data only.

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