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Abstract:

Dynamic behavior of a modified blade fitted onto a small 1 kW vertical-axis wind turbine is studied by two different approaches: Classical modal analysis (EMA) is carried out to validate the results of Operational Modal Analysis (OMA).

In traditional modal analysis (EMA) one axis accelerometers are mounted at different points on the projection of the centroid line of the blade structure. Measurements are set up in PULSE LabShop software (product of Brüel & Kjær Company). In each measurement set, one reference point is subjected to an impulse force, and acceleration responses are recorded at three different points. This process continues until the data set contains all the points with their degrees of freedom. Finally the frequency response function (FRF) is obtained for all points, and the natural frequencies and the mode shapes are estimated by peak picking method.

Operational Modal Analysis (OMA) is the second approach used in this project in parallel with stereo vision technique. In this method, only the output is required to be measured; actually the input is random and unknown. In this experiment markers are put on the blade centroid projection line (the same place as the accelerometer positions). The 3-D point deflections are monitored in time using stereo vision. Integration is not required for transforming acceleration to deflection in mode shapes identification because we will get deflection directly in this method. Two identical cameras take pictures of the blade and markers while it is excited by random and wind forces. The cameras are programmed in LabView to take pictures at the same time with 180 fps and store them on a high speed hard disk. The output deflection will be investigated in frequency domain by peak picking method, and then AR (Autoregressive) model is applied to describe the structure in time domain. Results of OMA and EMA show good agreement.

Keywords: Vertical axis wind turbine, Operational modal analysis, classical modal analysis, Peak picking, Autoregressive models

1 Introduction

Wind energy is receiving more attention in news media and politics. Application of vertical-axis wind turbines (VAWTs) in urban environment has triggered new ideas to approach, and novel designs have been realized by companies such as Turby, QuietRevolution and Venco using helical shaped rotor blades. In comparison with horizontal-axis turbines VAWTs can operate independently from wind direction changes and can endure temporal changes in the vertical wind speed in pitch and roll [1].

Structural and modal properties identification is one of the most important issues regarding the health monitoring of big structures such as wind turbines. Traditional modal analysis has some limitations: it needs artificial excitation of the structure to measure FRF, which is difficult to achieve on large structures. In Operational Modal Analysis the structure is not shaken and it will be excited by distributed and uncorrelated wind forces [2]. Therefore this method has been implemented on a wind turbine blade in this paper to be compared with the classical modal test which is done as well.

Using deflections instead of acceleration as the output is easier, more precise (direct measurement) and cheaper in terms of measurements for the following reasons: measuring acceleration needs two integration calculations to obtain displacements, and a scheme to iterate the two constants. This reduces the precision in comparison with measuring deflections directly. In the case of installation there are practical difficulties associated with acceleration measurements, e.g. installing lots of accelerometers, cables and power supply that costs time and money for installation on large structures like wind turbines. However, in stereo vision we use paper markers as 3-D sensors. The installation of many sensory markers needs no long preparation time. By mounting two identical equipped cameras which are looking onto these markers applied on the structure, the displacements can be found by a proper image processing algorithm. This technique is called stereo vision. Stereo vision has been used for measurements in wind turbines at Risø Campus of DTU. Paulsen *et al.*, in their recent studies on wind turbines, have indicated that full-field optical techniques, particularly stereo photogrammetry and videogrammetry systems, have some intrinsic features and capabilities that are extremely advantageous for the present challenge of measuring the operational deflection shapes of huge rotating objects [3].

2 Classical Modal Analysis(EMA)

In this part the structural properties of a modified blade fitted on a small 1 kW vertical-axis wind turbine, with 2m rotor diameter -is studied by monitoring of the acceleration on 24 points on the blade centroid line (Figure 1).

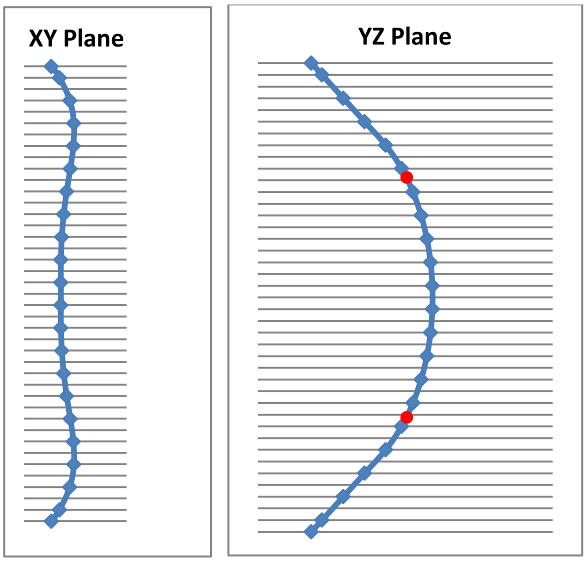

Figure 1 : 24 Accelerometers positions (blue points) and two support points (red points); vertical axes represent the y direction and horizontal axes represent x and z directions respectively.

The accelerometer instrumented blade is placed horizontally on two symmetrically spaced supports (red points in Figure 1). The blade is resting with its weight on the supports which can rotate around the X-axis and around the Y direction. Actually these points are representing the hinge position on the real wind turbine (Figure 2).

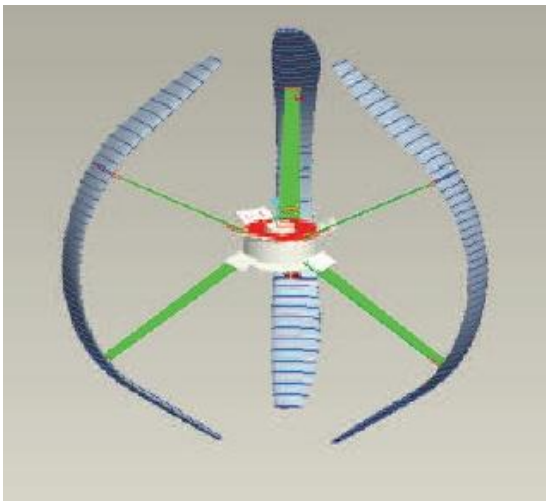

Figure 2: Rotor

36 sets of measurements are organized in Pulse and 3 points are measured in each set while the blade is hammered. In first 18 sets the blade is hammered in point 14 and accelerometers move around and measure acceleration in Y and Z directions with sampling frequency of 256 HZ. In the next 18 sets the blade is hammered in point 24 and the accelerometers move along the blade (Figure 3).

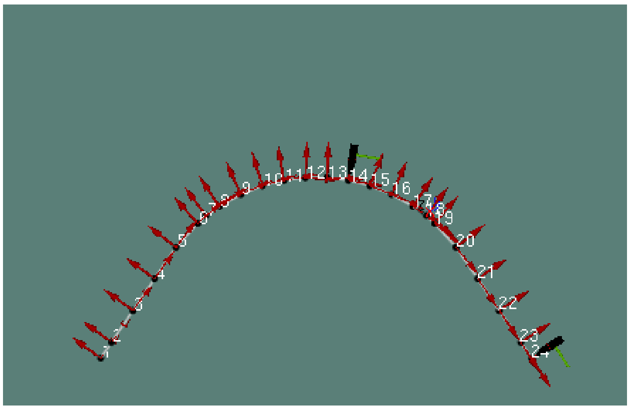

Figure 3: Measurement setup in YZ plane

The Frequency Response Function (FRF) obtained in every point is investigated for the identification of natural frequencies and derivation of associated mode shapes The FRF functions in two points are seen in Figure 4.

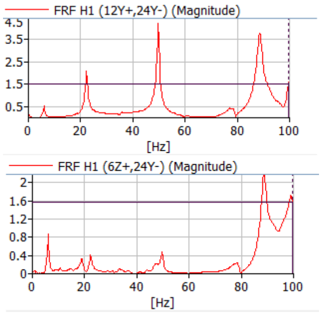

Figure 4: FRF function in point No.12 and 6

By looking at the FRF function, some peaks are obvious in the plots. The structure displacement will be large at or near natural frequencies [4]. In this case peak picking method is applied by moving around the peaks within+-10% of the peak frequency and finding expected mode shapes. The mode shapes and natural frequencies obtained by peak picking are estimated as follows:

Mode No.	**1**	**2**	**3**	**4**	**5**
Natural Freq. (HZ)	6.5	15	22	44.5	90

Table1: Natural frequencies by classical modal Analysis

It can be seen from figure 5, that the structure is almost fixed at the support points (between points 7 and 8 and points 17 and 18, shown in Figure 6), so the hinges are approximate node points. In other worlds as it has been mentioned before the structure moves slightly in the supports but their deflection is small regarding to other points. Furthermore all the modes are similar to the beam fixed on two points.

The acceleration responses obtained at the points in the same half area with the hammering point are affected by the hammering. In fact the hammer impact is added to the response. Therefore the response in the other half of the blade is considered.

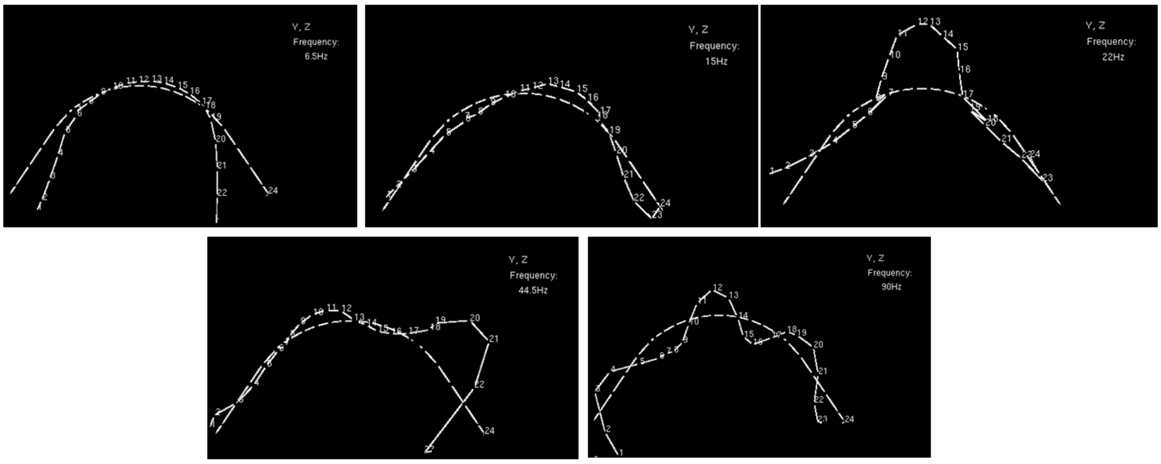

Figure 5: First 5 mode shapes by peak picking method

3 Operational Modal Analysis (OMA)

In OMA test, the blade is set outside in the field with the same boundary condition and supports as the EMA test. Markers are put on different positions of half of the turbine blade centroid projection line, and their 3-D deflections are recorded with a stereo vision system (Basler acA2040-180km), which are looking onto half of the blade while it is excited by the wind and other environmental forces. The experiment setup is shown in the Figure 6 and 7.

Figure 6: Experimental setup for OMA (Y-axis is the same as EMA but X-axis is Z- axis of EMA)

Figure 7: blade and hinges configuration

In a post process analysis, the mode shapes will be extracted from the deflection values without knowing the input. The first step before measuring is the camera calibration which is done by putting a plain (90 cm × 120 cm) board as shown in Figure 8.

According to the flat calibration plane, real positions of e.g. crosses are correlated with the camera CCD pixel information with a transformation.

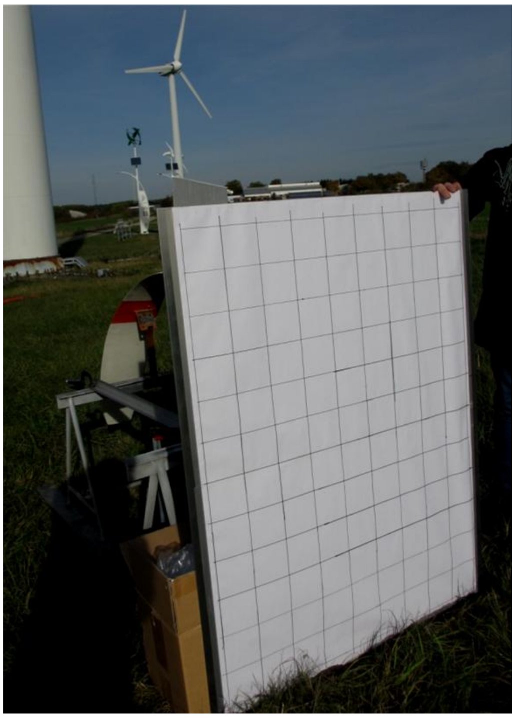

Figure 8: Calibration plate

The calibration matrix will be obtained, which includes rotational and translation matrix of the camera frame regarding to the real world, and some camera intrinsic information like focal length, chip size, and lens distortion.

3.1 Stereo vision

Stereo extracts 3-D information from two or more images taken from an object from different viewpoints. In stereo vision, the problems of correspondence and reconstruction should be solved [5].

The correspondence problem deals with finding the image points which are showing the same features. There are 2 different approaches to find corresponding points: correlation based methods which are used for dense disparity maps and images with lots of moving points close together. Featured based methods which are used for sparse disparity maps and images with a few moving points with special features like round or square objects [5].The latter method is used in this study.

In the reconstruction part 3-D coordinates will be calculated by knowing the position differences of identical points in 2 or more images (disparity map). Actually if the geometry of stereo system is known (which is defined by camera calibration) disparity map can recover the 3-D coordinates [5].

In the current study, the camera system is operating with a rate of 180 fps. Data acquisition has been programmed in LabView to take pictures of one half of the blade located about 5.8 m away from the cameras. The wind speed was about 8 m/s perpendicular to the blade tip. Alternatively, the structure was exited by soft hits from fingers. The following image shows images taken by stereo system:

Figure 9: Stereo image pair of blade

As the first step in correspondence part, the images are divided to 11 parts, each containing one marker:

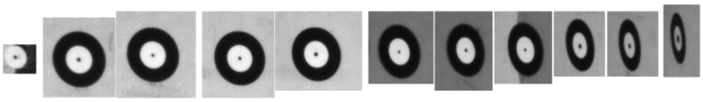

Figure 10: Windowing the images

There are just 11 points which do not move too much and will stay in the same windows all over the experiment. This is why the corresponding points have been already defined by defining a subset (windowing): For instance the first window contains the tip area in both images. In this sense we are using a feature based method(edge detection) to detect the middle point in the markers which will be followed in time. First of all the round edges are detected by gradient based algorithms then the smallest closed round object will be taken:

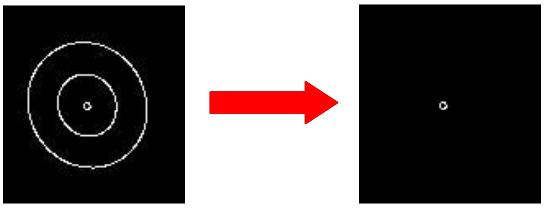

Figure 11: smallest round feature detection

As it can be seen in next image this method works well to recognize the markers in image:

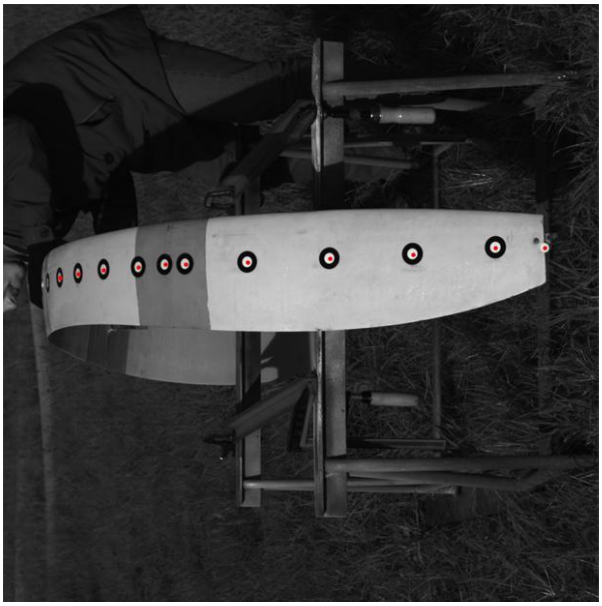

Figure 12: Point detection over the blade

3.2 Power Spectral Analysis

Examples of deflection of points over the blade in y (horizontal direction in the image) and x (depth direction in the image)directions are presented in Figure 13, each time step is equal to 1/180 sec. which means the deflections are recorded for 16.66 seconds (3000 time step).

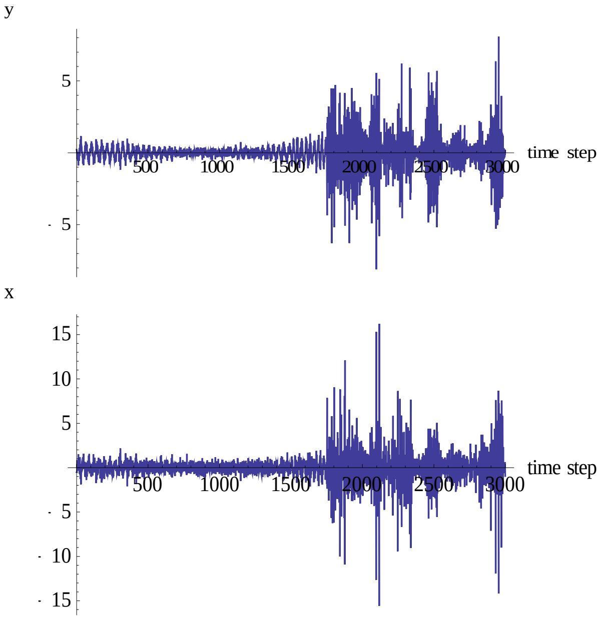

Figure 13: Tip point deflection time series

In Operational Modal Analysis the power spectrum density (PSD) is used for studying the output in frequency domain [6]. PSD and CPSD (Cross Power Spectrum Density) are calculated by Bartlet's method. In this method the signal has been divided into several segments and the power spectrum is averaged in segments to reduce the noise [7]. In this study 500 segments has been chosen. In Figures 14 and 14, PSD and CPSD (Cross Power Spectrum Density) are plotted in Nyquist frequency range which is half of the sampling frequency (180 Hz).

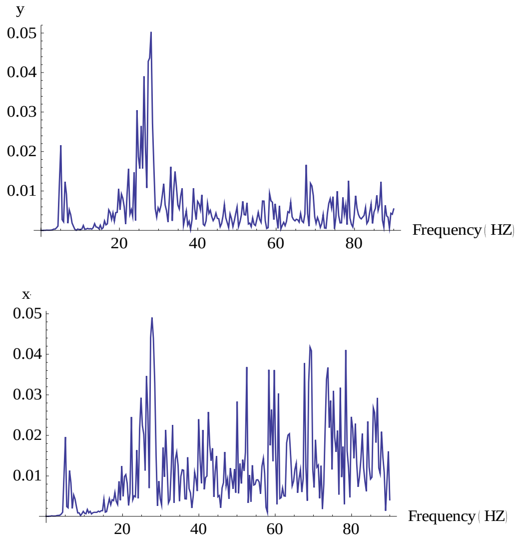

Figure 14: PSD obtained in tip point

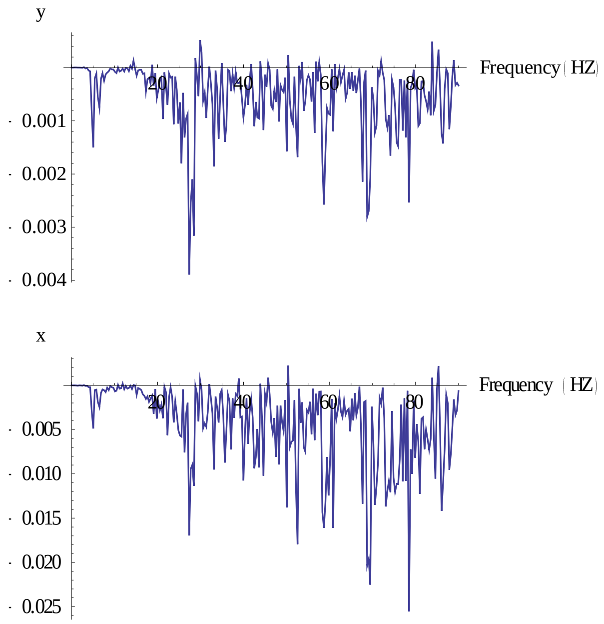

Figure 15: CPSD in one point after hinge

The peak picking method is one of the simplest ways to identify the modal properties such as natural frequencies and mode shapes [8]. A peak in the PSD will determine natural frequencies and the area under the PSC or CPSD plots around the resonance frequency is presenting the variance squared or mode shape squared in PSD and mode shape in CPSD. As it is seen in Figure 14 and 14 there are a few clear peaks in PSD and CPSD plots (especially in x- direction), but the time signal shows sudden changes in random excitation loading, it might be why the PSD diagrams could not show all of the modes sharply. Furthermore peak picking method does not work well in natural frequencies which are so close and are not well separated. Therefore an autoregressive model is implemented on this non stationary signal.

3.3 Autoregressive Model

The time domain is a very good choice for studying operational modal analysis. Actually a discrete-time system in state space will be described by state equation (eq. 1) which defines dynamic behavior of the system and the observation equation which relates output and input (eq. 2) [9]:

$$x(t_{k+1}) = Ax(t_k) + Bu(t_k) \tag{1}$$

$$y(t_k) = Cx(t_k) + Du(t_k) \tag{2}$$

Where $x(t)$, $y(t)$ and $u(t)$ are state matrix, output and input respectively. By assuming the input as white Gaussian noise and coupling these equations, it is realized that output in each time step can be constructed by the output in previous time steps and the input.

ARMA seems a proper method drive the coefficients which study dynamic behavior of a structure in time domain. This model is relating the time variables as following [9]

$$\begin{aligned} &y(t) - a_1 y(t-1) - a_2 y(t-2) - \ldots - a_p y(t-p) \\ &= w(t) + c_1 w(t-1) + c_2 w(t-2) + \ldots + c_q w(t-q) \end{aligned} \tag{3}$$

Where $y(t), w(t), a_i, c_i$ are the output, excitation autoregressive coefficients and moving average coefficients of the model, p, q are the model orders.

In operational modal analysis the excitation is unknown so it is assumed to be a random Gaussian white noise. Since the moving average part of the ARMA model is an infinite order autoregressive model, ARMA could be converted to a high order AR model [10]:

$$y(t) - a_1 y(t-1) - a_2 y(t-2) - \ldots - a_p y(t-p) = e_t$$

(4)

That e_t is the Gaussian white noise.

In AR(p) model (p is the model order number), companion matrix for discrete time series is equal to:

$$A = \begin{pmatrix} 0 & I & 0 & 0 \\ \vdots & 0 & \ddots & \vdots \\ 0 & \vdots & & I \\ a_p & a_{p-1} & \cdots & a_1 \end{pmatrix} \tag{5}$$

Where last row is the Autoregressive coefficients.

Autoregressive coefficients are fitting a proper polynomial to the time series, so that the companion matrix reveals the modal properties of the structure by the following eigenvalue problem

$$[\lambda, V] = eig(A) \qquad (6)$$

Then Natural frequencies and damping ratios are given by [9]:

$$f_i = \frac{\left|\frac{\ln(\lambda_i)}{T}\right|}{2\pi}$$

$$\xi_i = \frac{\mathrm{Re}\left(\frac{\ln(\lambda_i)}{T}\right)}{\left|\frac{\ln(\lambda_i)}{T}\right|} \qquad (7)$$

Where T is the sampling time step;

Figure 16 is presenting how autoregressive coefficients build up the time signal:

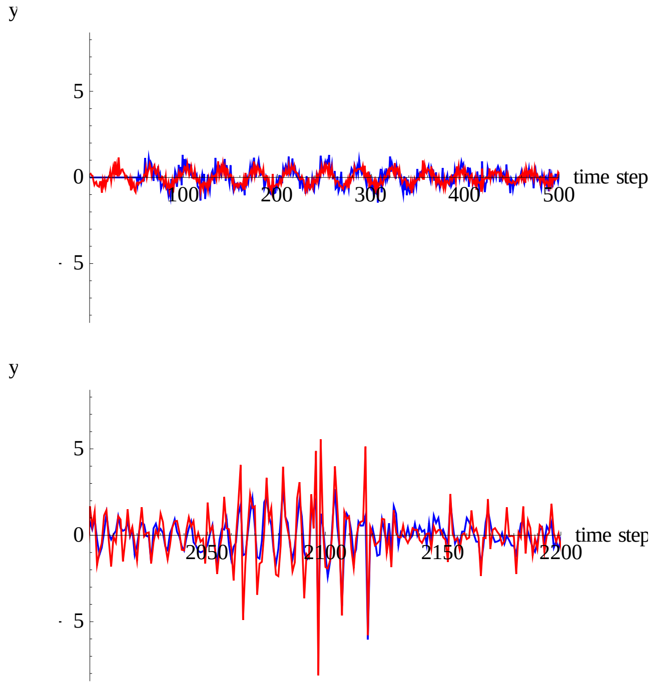

Figure 16: Red line is the time series and blue line is curve generated by AR(50), top Figure shows deflection in first 2.77 seconds and bottom figure shows deflection since t=11.11s until t=12.22s

4 Modal Identification Results

Eigen frequencies and mode shapes are identified by peak picking and high order AR method for half of the blade. As the picks are not sufficiently sharp to identify the damping ration by peak picking method, damping ratios in first 5 modes are only calculated by AR method:

Mode No.	**1**	**2**	**3**	**4**	**5**
Natural Freq. (Hz) EMA	6.5	15	22	44.5	90
Natural Freq. (Hz) OMA - Peak Picking	4.75	19	26.65	41	61
Natural Freq. (Hz) OMA - AR	4.89	22.31	25.5	40.96	60.17
Damping ratio OMA - AR	2.43%	0.91%	1.06%	1.06%	0.64%

Table1: Natural frequencies by different methods and damping ratios by AR method

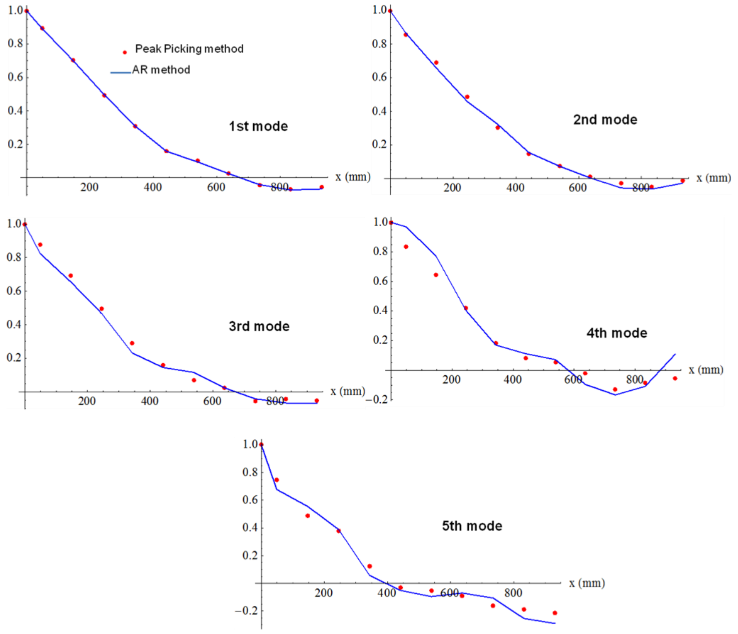

Figure 17: mode shapes by peak picking and AR methods (X axis are showing Point positions along Y-axis)

It is obvious from table 1 that natural frequencies obtained by all methods agree well in the first 4 modes but modes 2 and 3 are so close and not well separated in PSD plots, in addition mode 3 well picked and it is why there is a little difference in natural frequency in the second mode for all methods.

From the table, the fifth mode show rather big difference between EMA and OMA frequencies. PSD plots could indicate that the highest frequency has not been exited during random excitation. It is not selected sharply, which for an application could lead to some problems in natural frequency identification in OMA. Another reason for missing the last natural frequency is short sampling time (16.66s) which it needs to be longer to have more accurate results. In addition the Nyquist frequency of 90 Hz makes it difficult in identifying this mode. In comparison with EMA, the frequency determination for the last mode might be more reliable. On the other side, the other mode shapes show good agreement (Figure 17).

5 Conclusion

Vertical Axis Wind Turbines (VAWT) is under renewed interest for their potential use and wind direction insensibility of turbulent wind [1] at urban sites, in comparison with the Horizontal Axis Wind Turbines (HAWT). In the current study, the dynamic behavior of a modified VAWT blade intended to be mounted on a modified blade fitted onto a small 1 kW sized wind turbine is investigated structurally by two different approaches: Traditional and Operational Modal Analysis (EMA and OMA). In EMA both input and output are used to identify the modal parameters but In OMA the output is only measured. On the other hand the input is random and distributed and the output is used for estimating the modal parameters [2].

For this study in the EMA test, there are some known difficulties in the EMA test, such as that the hammer impact affects the recorded response signals. In conclusion OMA has been proposed to avoid these kinds of difficulties. In the current OMA test the blade is tested in the open air, excited by wind forces. The deflections of a few points on the blade centroid line are monitored using stereo vision technique. In this technique two cameras are looking at the moving points in time, so by intersecting two sight lines 3-D coordinates are determined. The point deflection is used as the output for OMA and will be analyzed to estimate modal shapes and natural frequencies. Results of these two different approaches are showing good agreement in terms of mode shapes. However, natural frequency determination shows a difference in fifth mode in comparison with the applied methods which can be because of short data acquisition time and rather low sampling frequency.

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