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WIND TURBINE MASS AND AERODYNAMIC IMBALANCES DETERMINATION

Nduwayezu Eric* and Mehmet Bayrak
Department of Electrical Electronics Engineering, Sakarya University, Turkey

ABSTRACT

This paper evaluates the use of simulations to investigate wind turbine mass and aerodynamic imbalances. Faults caused by mass and aerodynamic imbalances constitute a significant portion of all faults in wind turbine. The aerodynamic imbalances effects such as deviations between the three blades pitch angle are often underrated and misunderstood. In practice, for many wind energy converters the blade adjustment is found to be sub-optimal. The dynamics of a model wind turbine was simulated in three different scenarios that are normal operating conditions, blade imbalance, and aerodynamic imbalance. Blade element momentum method was used to determine the effects of blade deviations. The blade imbalance was simulated by scaling the mass density of one blade, which creates an uneven distribution of mass with respect to the rotor. The results showed that an aerodynamic imbalance fault varies with rotor speed and wind velocity. They also reveal the extent of energy loss and additional loads. These conclude that, unlike mass imbalance, aerodynamic imbalance can't be eliminated by counterweights. The balancing of the rotor requires a method to determine its imbalances. This paper proposes also a methodical system for the reconstruction of two types of imbalances that are, mass and aerodynamic imbalances from pitch angle deviation. The methodical system with simple finite element will be based on the inversion of the (nonlinear) operator equation that links the imbalance distribution of the rotor to its vibrations during operation of the wind turbine. This methodical system will enable to eliminating aerodynamic imbalances which leads to a maximized life time of blades, drive train, main frame and tower.

KEYWORDS: Wind turbine, mass and aerodynamic imbalance, blade, pitch angle, regularization.

INTRODUCTION

In the development of wind energy extraction, the topic of aerodynamic imbalances of wind turbine is of serious importance for the operation, safety, and durability of the wind turbine. Imbalance faults constitute a significant portion of all faults in wind turbine [3]. A common imbalance fault in wind turbine is blade imbalance. A blade imbalance can be caused by errors occurred in manufacturing and construction, icing, deformation due to aging, or wear and fatigue during the operation of the wind turbine. As many wind turbines are situated on high towers, installed in remote rural areas, and distributed over large geographic regions, inspection and maintenance for the wind turbines requires significant effort and cost. Engineers have reported that the operation and maintenance cost can account for 10–20% of the total cost of energy for a wind project [1]. Moreover, wind on the supporting tower of the wind turbine, which may lead to fractures and possible collapses [4] of the tower. In common practice, imbalance measurements are often carried out only with respect to an overall value of rotor imbalance. The fact is that the rotor imbalances can have different characteristics as explained above. It is a meaningful reason to determine whether the imbalance's origin lies in an uneven distribution of the rotor mass that is mass imbalance or in a deviation of the aerodynamic properties of the three blades, for instance different settings of the blade pitch angle that is aerodynamic imbalance. The distinction between mass imbalance and aerodynamic imbalance is a prerequisite for finding suitable measures of optimization. The main reason for aerodynamic imbalance is a relative deviation of the pitch angles of the blades as stated

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above. This can only be eliminated by a correction of those angles. Additional masses are not much helpful here [5]. Practically, both types of imbalances are frequently observed both separately and in combination. Often, the detection of imbalances is based on spectral analysis and order analysis methods [6]. Another technique is to monitor the power characteristic [7], whereby power mean values are observed, and deviations from faultless conditions are used for the calculation of alarm limits. Unfortunately, this requires a learning phase under faultless conditions. This also holds for other signal processing methods [6]. Another disadvantage is the fact that the amount of the imbalance, for instance absolute value and location of a mass imbalance or the deviation of one or more pitch angles, is not computable. In the present paper we consider a model that allows for a reconstruction of both mass imbalances and aerodynamic imbalance caused by deviations in pitch angles at the same time. Since aerodynamic imbalances also cause vibrations in axial directions and torsional vibration around the tower axis; we have expanded our turbine model in these dimensions. To describe the forces and moments from aerodynamic imbalances we have used the blade element momentum method. Due to the blade element momentum method, the direct problem of relating the imbalance cause (here the pitch angles deviation and a mass imbalance) to the vibrations of the turbine becomes non-linear. However, the regularization techniques for solving the inverse problem also apply to non-linear problems. To ensure a good imbalance reconstruction we observed that the initial value should already be a fairly good idea for the mass imbalance, which we obtained by our method described above that will be developed in details in this paper by assuming the absence of aerodynamic imbalances. We reconstructed a good idea for the mass imbalance from the lateral vibrations neglecting the influence from the pitch error. The result is surely not the correct mass imbalance but serves very well as an initial value for the reconstruction of both imbalance causes.

WIND TURBINE STRUCTURAL MODEL

Mass and Stiffness Matrix

While thinking about reconstructing imbalances from vibration measurements we must be able to handle the other direction, like to compute the resulting vibrations of the wind turbine tower for a given imbalance cause.

In order to establish appropriate mathematical equations we have to first derive simple assumptions. First we assume that the wind turbine is a flexible shaft (the tower) with an additional mass (the nacelle and the rotor) at the top point, where one part of that mass (the rotor) rotates with a rotational frequency. The movement of such a shaft is explained by a partial differential equation in time and space. Using finite element methods, the energy formulation can be transformed into a system of ordinary differential equations. The ordinary differential equation system connecting dynamical loads and object displacements has the form:

$$M\frac{\partial^2 u}{\partial t^2}+Su(t)=p(t)$$

Where M is the mass or inertia matrix, S the stiffness matrix, u the vector of the degree of freedom and p the load vector. In the finite element method approach, the wind turbine is divided into elements which are in our case hollow cylinders. The movements in lateral or z-direction, in axial or y-direction and torsional movements around the x-axis (see Figure 1) for the coordinate system are considered. There are no movements in x-direction since the tower is supposed to be rigid against shear forces.

For each node we only consider the degree of freedom (ω, β_z). In order to construct the mass and the stiffness matrix each element is treated separately. The degree of freedom of the bottom and the top node of the i^{th} element are collected in the element degree of freedom vector.

$$u_e^i= [\omega_{0i} \;\; \beta_{z0i} \;\; \omega_i \;\; \beta_{zi}]^T.$$

The derivation of the element mass and stiffness matrix Me and Se uses four shape functions scaled by

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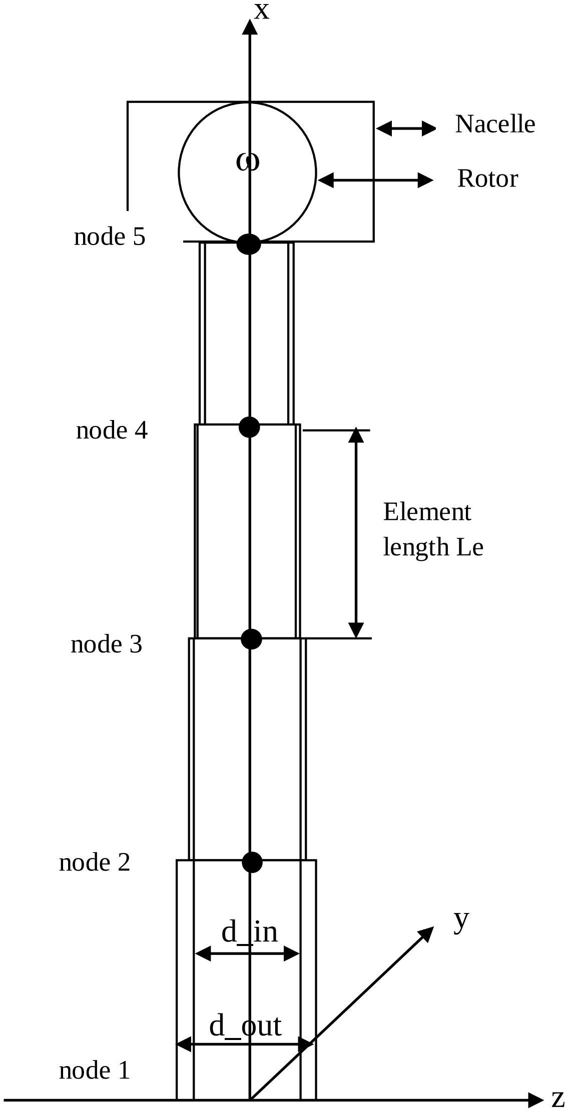

Figure 1. Model of wind turbine.

the degree of freedom of an arbitrary point x of the element.
It is given in detail in [8]. We only want to present the final mathematical expressions for the element matrices,

$$Me=\frac{\mu Le}{420}\begin{bmatrix}156 & -22Le & 54 & 13L_e\\ -22L_e & 4L_e^2 & -13L_e & -3L_e^2\\ 54 & -13L_e & 156 & 22L_e\\ 13L_e & -3L_e^2 & 22L_e & 4L_e^2\end{bmatrix},$$

$$Se=\frac{E.I}{L_e^3}\begin{bmatrix}12 & -6L_e & -12 & -6L_e\\ -6L_e & 4L_e^2 & 6L_e & 2L_e^2\\ -12 & 6L_e & 12 & 6L_e\\ -6L_e & 2L_e^2 & 6L_e & 4L_e^2\end{bmatrix}$$

The length of the element that will be discussed in the next paper is represented by Le. E is Young's modulus, which is a material constant that is found in a table. Our elements are assumed to be circular beam sections. The moment of inertia I is given by: $I=\frac{\pi}{64}(d_{e,out}^4 - d_{e,in}^4)$ where $d_{e,out}, d_{e,in}$ are outer and inner diameter of the beams section respectively. μ is the translatorial mass per length $\mu = \rho.A$, where ρ is the density of the material. $A=\frac{\pi}{4}(d_{e,out}^2 - d_{e,in}^2)$ is the annulus area. Creating the full system matrices S and M, the element matrices Se and Me are combined by superimposing the elements affecting the upper node of the i^{th} element matrix with the ones belonging to the lower node of the (i + 1)st element matrix. The sum of rotor mass and nacelle mass m needs to be added to the last but one diagonal element of the full mass matrix.

INVERSE PROBLEM

Within this Section, we have established the theory of treating (non-) linear ill-posed problems. We assume that the connection of two terms f and g such as an imbalance and the displacements resulting from that imbalance, is described by an operator **A**:

$$A.f=g$$

The problem is called ill-posed, if the solution f does not depend continuously on the data g. The forward problem while the determination of f for given g is referred to as the inverse problem. In practical applications the exact data of g are not known but a measured noisy version g^{δ} of that data. We assume that the noise level is bounded by an unknown number δ, that is $\|g- g^{\delta}\| \le \delta$, then (provided the inverse A^{-1} exists) $f^{\delta} = A^{-1}g^{\delta}$ might be an arbitrarily bad approximation to a solution of A.f=g. To obtain a stable solution, we used the so called regularization methods[15]. The general idea is to approximate the discontinuous inverse operator by a family of continuous operators T_{α}. The computation of an imbalance from vibration/displacement data is an inverse problem. If the following three conditions are fulfilled[18], the Inverse Problem is called well posed:

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(a) For all data of g there exists a solution f.
(b) The solution of f is unique.
(c) The solution of f depends continuously on the data g. (A^{-1} is continuous.)

The last condition ensures that small changes in the data g result in small changes in the solution f. A well posed inverse problem can be solved by applying the inverse operator to the data:

$$f = A^{-1}g.$$

If one of the conditions is violated the inverse problem is called ill-posed. The regularization parameter α has to be chosen such that $\lim_{\delta\to 0} \alpha(\delta, g^{\delta})=0$ holds. For nonlinear operators, equation A.f=g might have several solutions[15]. Thus we choose the concept of a $\overline{f}$ minimum-norm solution as if we are looking for a solution closest to a priory given function $\overline{f}$. A widely used example for a regularization method is Tikhonov's regularization where the operator $T\alpha$ is given by

$$T_{\alpha}g^{\delta}=f_{\alpha}^{\delta}=\operatorname{argmin}_{f} J_{\alpha}(f)$$

with the Tikhonov functional is given by

$$J_{\alpha}(f)=\| g^{\delta}-Af\|^2+\alpha\|f-\overline{f}\|^2$$

where **A** denotes a matrix. For the determination of the regularization parameter α we will use Morozov's principle. The computation of g for given f is called the well-known posteriori parameter choice rule of Morozov's discrepancy principle where α is chosen.

$$\delta\leq\| g^{\delta}-Af_{\alpha}^{\delta}\|^2\leq c\delta$$

holds [9,10]. A classical approach to minimize the functional $J_\alpha(f)$ is the use of gradient methods. The gradient of the Tikhonov functional is given by

$$\mathbf{T}_{\alpha} = (\mathbf{A}^{*}\mathbf{A} + \alpha\mathbf{I})^{-1}\mathbf{A}^{*},$$

where **I** is the identity and $\mathbf{A}^*$ denotes the adjoint operator of **A**. In case **A** is a matrix, $\mathbf{A}^*$ is the transpose of **A**. The application of the discrepancy principle requires the computation of the approximate solution f_{α}^{δ} for a chosen α first. Afterwards $\delta\leq\| g^{\delta}-Af_{\alpha}^{\delta}\|^2\leq c\delta$ is checked and α has to be

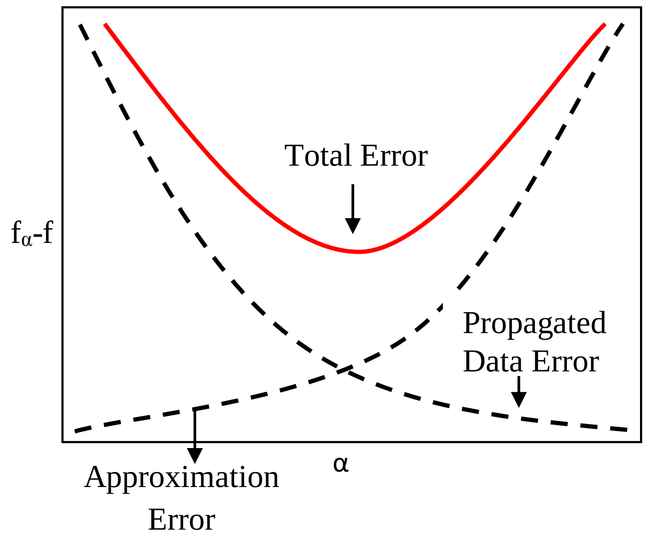

Figure 2. Regularization error

changed if the condition does not hold. All a-posteriori parameter choice rules depend on the data error level δ and the data g^{δ}. Very popular are heuristic parameter choice rules, where the regularization parameter is independent of the noise level δ. This is the fundamental estimate for a regularization strategy[16]. We illustrated this estimate by constructing a regularization strategy for the numerical differentiation problem using the central difference formula and the step size α as a regularization parameter.

IMBALANCES DETERMINATION

Imbalances determination from measurements of the induced vibrations or displacements is an inverse problem as stated above.

Mass Imbalance

In order to evaluate the magnitude of the mass imbalance, measurements of the tower-nacelle vibrations were performed after minimizing the aerodynamic imbalance by blade angle adjustment. Then, the total imbalance calculated from the measured vibration amplitude is equal to the mass imbalance. The knowledge of the mass and stiffness matrix provides us with a connection of the loads from imbalances **p** and the resulting displacements **u**

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in the nodes of our model via equation $M\frac{\partial^2 u}{\partial t^2}+Su(t)=p(t)$. A mass imbalance can be described by a mass m that is located at a distance r from the rotor center and has an angle φ to a certain zero mark of the rotor[13][14], If the rotor revolves with revolutionary frequency f, the mass imbalance induces a centrifugal force of absolute value ω^2mr, with the angular velocity $\omega = 2\pi$f. The force or load vector is given by:

$$p(t)= \omega^2 mr e^{i(\omega t+\varphi)}=p_0\, \omega^2 e^{i\omega t}$$

where p_0=mr$e^{i\varphi}$ defines the mass imbalance in absolute value and phase location. Harmonic loads of the form $p(t)= \omega^2 mr e^{i(\omega t+\varphi)}=p_0\, \omega^2 e^{i\omega t}$ cause harmonic vibration $\boldsymbol{u} = \boldsymbol{u_0} e^{i\omega t}$ of the same frequency ω. By inserting **u**, its second derivative and $\boldsymbol{p} = \boldsymbol{p_0} e^{i\omega t}$ into equation $M\frac{\partial^2 u}{\partial t^2}+Su(t)=p(t)$, time dependency cancels out and we get an explicit solution for the vibration amplitudes $\mathbf{u}_0$:

$$\mathbf{u}_0 = (-M+ \omega^{-2}S)^{-1}\mathbf{p}_0.$$

The matrix $(-M+ \omega^{-2}S)^{-1}$ would define our forward operator in equation A.f=g if we would assume that the vibration amplitudes could be measured in every node of the model. Usually this is not possible; measurements are taken in the nacelle which is represented by the last model node. Hence $f= p_0$, $g = u_0$ the displacement of the last node, and **A** is just the element in the last but one row and last but one column of $(-M+ \omega^{-2}S)^{-1}$.

Note that The forces caused by this mass are gravity and centrifugal force ω^2mr. The projections of this force into the z- and x-axis are:

$$(F_c)_z=F_c\cos(\omega t + \varphi + \varphi m)$$
$$(F_c)_x=F_c\sin(\omega t + \varphi + \varphi m)$$

where, t is time variable, and ϕ is the angle between blade A and the x-axis, (mr,φ_m) are absolute value and angle w.r.t. blade A of the mass imbalance, $\omega=2\pi f$ is the angular frequency (note: wind turbine rotates clockwise seen from the wind), $\varphi=\frac{4\pi}{3}$ is the angle between blades.

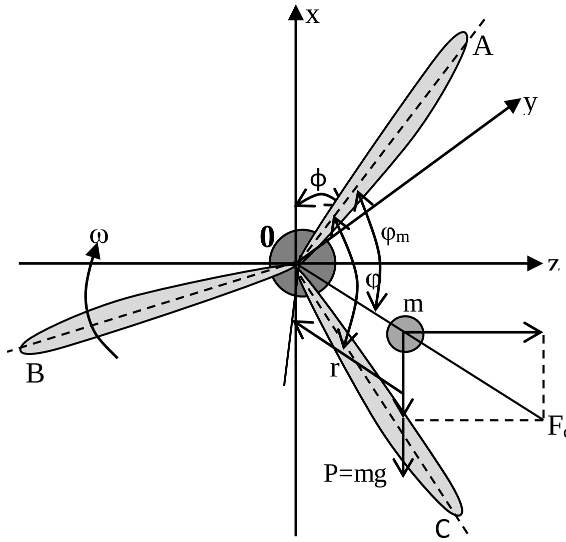

Figure 3. Mass imbalance model.

Since the rotational plane has a distance L(distance from hub to nacelle midpoint of *x*-axis) to the tower, the forces $(F_c)_z$ and $(F_c)_x$ produce moments around the x- and the z-axes with respect to the tower too

$$M_x^1 = (F_c)_z \cdot L$$
$$M_z^1 = (F_c)_x \cdot L$$

Furthermore, the gravity force of the point mass also creates a small moment around the z-axis. Unfortunately, this moment is not taken into account.

Aerodynamic (rotor) Imbalance from pitch angle deviation

The impact of rotor imbalance is found on all components. Rotor imbalances not only lead to the acceleration of component wear, but also to serious damage to major components such as blades, gearboxes, bearings and main frames. The extent of the damage depends on the level of the imbalance, as well as the period of time a turbine operates with a certain imbalance. The main cause for rotor imbalances is a deviation between the pitch angles of the blades, that may occurs from assembling inaccuracies[14]. Based on the wind conditions, even a small deviation of one of the pitch angles can cause large forces and moments to be transferred into the rotor. Operators should bear in mind that aerodynamic imbalances have a high damage potential due to their strong excitation of torsional

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vibrations. Furthermore, aerodynamic imbalances will reduce the energy yield of the wind turbine significantly. To describe the aerodynamic loads on a wind turbine, we have employed the well-known blade element momentum theory [11, 12]. In the blade element momentum theory, we divide the blades into a finite number of elements which are sections of the blades into annulus segments with the center at the root of the blades. The cross section of each element is called "airfoil",

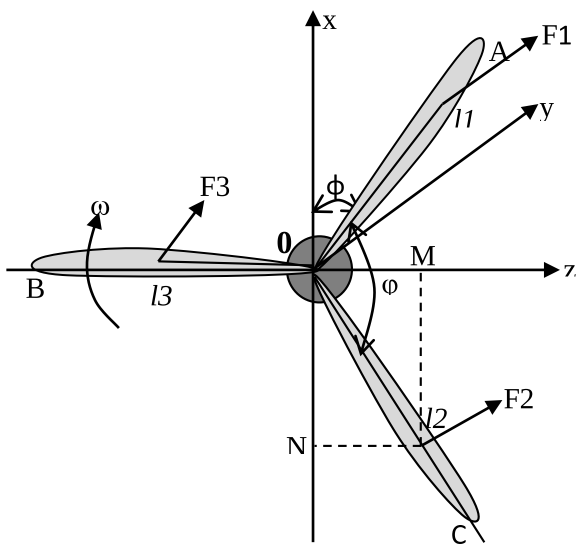

Figure 4. Thrust forces on the rotor blades.

The forces depend on the pitch angle of the blade, the airfoil data, the angle of attack of the wind, and the relative wind velocity, as well as a lift and drag coefficient table. The distributed forces are summed up to an equivalent normal force F_i with a distance l_i from the rotor center as well as an equivalent tangential force T_i.

Since the airfoil data, the angle of attack of the wind, and the relative wind velocity, as well as a lift and drag coefficient; we can calculate the thrust forces F and the tangential forces T according to the blade element momentum method, The local pitch angle θ for each blade element, which is the angle between chord and the plane of rotation, is the sum of the adjusted pitch angle θ_p at the blades root and the twist of the blade β:

$$\theta = \theta_p + \beta$$

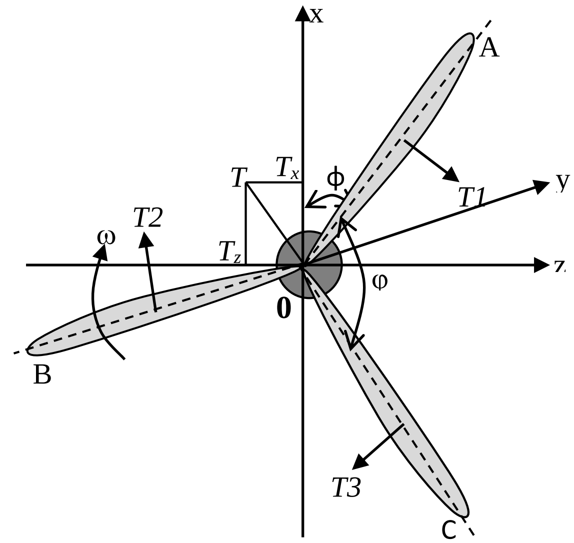

Figure 5. Tangential forces on the rotor blades

The results of this procedure are forces on each of the blades distributed over all blade elements as stated before.

The force to the rotor in the axial (y-) direction is calculated by:

$$F_y = F_1 + F_2 + F_3.$$

The moments induced by this forces are given by:

$$M_x^1 = F_1 l_1 \sin(\omega t+\phi)+F_2 l_2 \sin(\omega t+\phi+\varphi)+F_3 l_3 \sin(\omega t+\phi+2\varphi)$$

$$M_z^1 = F_1 l_1 \cos(\omega t+\phi)+F_2 l_2 \cos(\omega t+\phi+\varphi)+F_3 l_3 \cos(\omega t+\phi+2\varphi)$$

Note that if all blades have the same pitch angle, we have $F_1 = F_2 = F_3$ and $l_1 = l_2 = l_3$. This means that the moments M_x^1 and M_z^1 vanish. The projection of the total tangential force $T=T_1+T_2+T_3$ onto the z-axis and the x-axis is given by:

$$T_Z = T_1\cos(\omega t+\phi)+T_2\cos(\omega t+\phi+\varphi)+T_3\cos(\omega t+\phi+2\varphi)$$
$$T_x = T_1\sin(\omega t+\phi)+T_2\sin(\omega t+\phi+\varphi)+T_3\sin(\omega t+\phi+2\varphi)$$

As mentioned before we have a small distance *L* between rotor plane and tower center, thus T_z and T_x also produce moments around the *x*- and the *z*-axes:

$$M_x^T = T_z.L\ ,\ M_z^T = T_x.L$$

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From the formulas Fy = $F_1 + F_2 + F_3$, $M_x^T = T_z.L$, $M_z^T = T_x.L$ we can describe the load vector p(t) in equation $M\frac{\partial^2 u}{\partial t^2}$+Su(t)=p(t), which has only entries at the last node. We recall that the node has the degree of freedom (υ,ω, β_x, β_y, β_z), therefore

$$\mathbf{p} = (0, \cdot\cdot\cdot, 0, F_y, F_z, M_x, M_y, M_z)^T,$$

with $F_z = T_z + F_{c(z)}$, $M_x = M_x^1 + M_x^2 + M_x^3$ and $M_z = M_z^1 + M_z^2 + M_z^3$. We notice that M_y is converted into the rotational movement and finally into electrical energy that's why it doesn't add any contribution to the load vector.

BALANCING

By Starting from the pitch angles of the three blades (θ_1, θ_2, θ_3), and from the characteristics of a mass imbalance (mr, ϕ_m) and assuming the given values for angular speed $\omega = 2\pi f$, wind speed, and airfoil data. We have all the tools to determine the corresponding imbalance load **p** using the blade element momentum method for the pitch angle deviation and by projecting[13] $p(t) = \omega^2 mr e^{i(\omega t+\varphi)} = p_0\ \omega^2 e^{i\omega t}$ into the x- and the z-axis. Solving $M\frac{\partial^2 u}{\partial t^2}$+Su(t)=p(t) produces the resulting displacements **u**. Therefore it is necessary to restrict our solution to degree of freedom. We notice that the restricted vibration is $g = u_{sensor}$. The final forward operator A that relates the imbalances causes to the vibrations is the projection of:

$$\mathbf{A}(\theta_1, \theta_2, \theta_3, mr, \varphi) = \mathbf{g}.$$

Unfortunately, this operator is nonlinear due to the blade element momentum method. This property will determine the possible solution methods for the inverse problem of reconstructing (θ_1, θ_2, θ_3, mr, φ) from measurements of g. For a known or estimated noise level δ of the measurements we can compute the solution $(\theta_1, \theta_2, \theta_3, mr, \varphi)_\alpha^\delta$ as the minimizer of the Tikhonov functional $J_\alpha(f) = \| g^\delta - Af\|^2 + \alpha\|f - \overline{f}\|^2$ Since **A** is a nonlinear operator, the minimization methods have to be employed to find the minimizing element, like the Matlab implemented routines like fminsearch. fminsearch which uses the simplex search method which is a direct search method. The regularization parameter α has been chosen iteratively using Morozov's discrepancy principle $\delta \le \| g^\delta - Af_\alpha^\delta\|^2 \le c\delta$. The computational simulations and results have been obtained after we have tested the performance of the reconstruction technique for a Bereket Enerji's turbine of the type SINOVEL SL1500/82-1.5MW installed at Uşak wind power plant with 100 m tower height and artificial data implemented. We achieved the artificial data by employing the forward operator $\mathbf{A}(\theta_1, \theta_2, \theta_3, mr, \varphi) = \mathbf{g}$ for a given imbalances situation. The exact vibration data were disturbed by an additive and multiplicative error in order to simulate the noise that arises in measurement. The following parameters have been employed:

-Construction of mass and stiffness matrix using the technical parameters of the SINOVEL SL1500/82-1.5MW(eigenfrequency 0.317 Hz)

- Setting of a 2^0 pitch angle deviation at the blade C and a mass imbalance of 500 kgm at angle $\varphi = \frac{4\pi}{3} = 240^0$: $[\theta_1, \theta_2, \theta_3, mr, \varphi]$=[0,0,2,500,240]

-rotational speed f=17.4rpm

-Adding 10% noise to the data to simulate the measurements

-Calculate an approximate solution $(\theta'_1, \theta'_2, \theta'_3, mr', \varphi')$ by minimizing the functional $J_\alpha(f) = \|g^\delta - Af\|^2 + \alpha\|f - \overline{f}\|^2$ with an appropriate regularization parameter

-Rotor diameter (m) is 82.9m,

-Swept area (m^2) is 5398m^2

-Height of hub (m) is 100m

-Average wind speed is 7.5m/s

-Wind Turbine class IECII / IECⅢ

For our computation tests, we set the exact parameters $[\theta_1, \theta_2, \theta_3, mr, \varphi]$=[0,0,2,500,240] We have employed Tikhonov regularization for all kind of data. However, in practice only the displacements in y- and z- direction at the top of the tower are available. In the first attempt, the result is not the true mass imbalance but a sufficiently accurate initial estimate for the simultaneous reconstruction was carried out as a second step[19]. Tikhonov regularization with $\alpha = 10^{-6}$ was used for all reconstructions. The error is split into two parts related to aerodynamical and mass imbalances:

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$$\frac{||(\theta_1,\theta_2,\theta_3)-(\theta'_1,\theta'_2,\theta'_3)||}{||(\theta_1,\theta_2,\theta_3)||}.100\%$$

and

$$\frac{||mr.e^{i\varphi}-mr'.e^{i\varphi'}||}{||\mathrm{mr}.e^{i\varphi}||}.100\%$$

Here $(\theta'_1,\theta'_2,\theta'_3,\mathrm{mr}',\varphi')$ refers to the reconstruction and $(\theta_1,\theta_2,\theta_3,\mathrm{mr},\varphi)$ is the exact parameter vector.

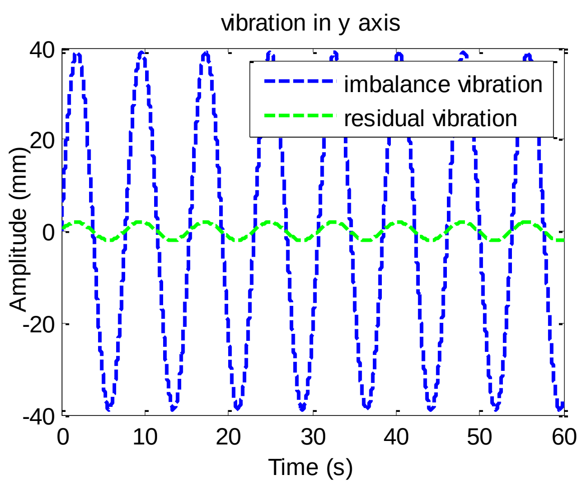

Figure 6. Imbalance vibration and residual vibration across y-axis (on the top of the tower).

Measurement in	**Initial value**					**Noise in %**
All nodes	0	0	2	500	4	no
						yes
	0	0	0	0	0	no
	0	0	0	450	4	no
						yes
-y,-z displacement	0	0	0	0	0	no
	0	0	0	420	1.7	yes

result					**aero error%**	**mass error %**
0	0	2	500	4.19	0	0
0.12	0.05	2.08	500.3	4.19	7.4	0.06
-6.1	4.57	2.64	307.6	-2.32	382	42
-0.81	-0.3	1.98	502.9	4.19	43	0.6
-0.02	-0.88	1.96	504.9	4.2	44	1.4
-3.05	-3.05	1.54	83	-2.2	216	84
0.37	-0.92	1.75	491.7	4.19	51	1.66

Table1. Results with Tikhonov's regularization algorithm.

The results in Table 1 show that the quality of the reconstruction depends on the initial value for the reconstruction. Good initial values, in particular for the mass imbalance; lead to good reconstructions.Reconstructing mass imbalances only, is inaccurate if we neglect existing of aerodynamic imbalances. However, it could provide us with an approximate mass imbalance that serves well as an initial guess for our new algorithm[17]. To finalize this algorithm we have taken a pitch angle deviation of $3^0$of the blade B as well as a mass imbalance of 350 kgm located at blade B. The data **g** were calculated by the forward computation of **A**(0^0, 3^0, 0, 350 kgm,120^0) and contaminated with 10% noise. The two step reconstruction from the noisy data resulted in **A**(-0.25^0, 2.8^0, 0.43, 342kgm,121^0).

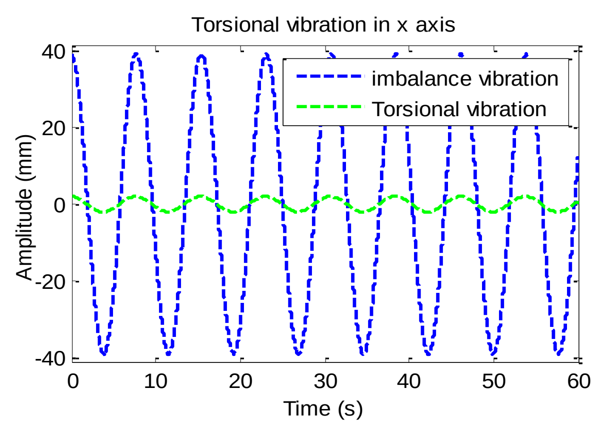

Figure 7. Imbalance vibration and Torsional vibration across x-axis (ideal).

The last result is calculated by using the initial value from the above mentioned algorithm. The performance of the algorithm was tested on several other experiments as seen in the table 2.

Original Parameters	**Initial values**
[0 3 0 350 2.09]	[0 0 0 647 2.09]
[2 -2 0 400 1.05]	[0 0 0 798 1.05]

reconstructed parameters					**aero error %**	**mass error %**
-0.25	2.8	0.43	342	2.1	17	2
1.99	-0.64	-0.06	402	1.05	48	0.5

Table 2. Results test with Tikhonov's regularization and fminsearch

In these examples, we have used vibrations of the top of the tower as artificial data. The data were

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disturbed by 10% noise. With the help of balancing principle, we have made a variation on the mass and aerodynamic imbalance in the first example according to the reconstruction (using the last reconstruction in Table 1). Therefore, the new pitch angles are given by [0, 0, 2] − [0.37, −0.92, 1.75] = [−0.37, 0.92, 0.25], and the residual mass imbalance is computed by $500e^{i4\pi/3} + 491.7e^{i(4.1929-\pi)}$. Here, it is 8.5 kgm located at the phase angle −2.33 rad or 226.5^0. Practically this is achieved by placing extra weights on the blades. Using these new parameters we have shown the correction of the pitch angles and the setting of balancing weights according to that reconstruction lead to a significant reduction of the vibration as shown in figure 8.

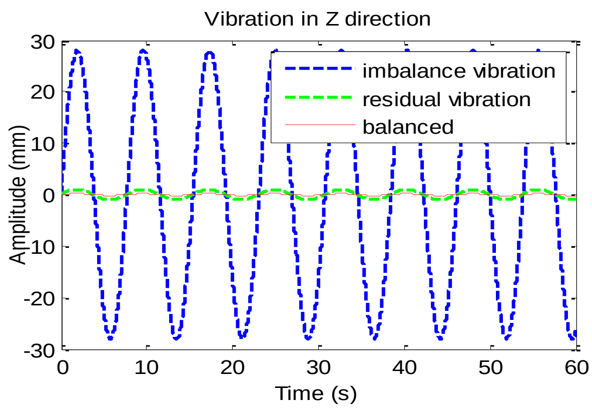

Figure7. Vibrations in z-direction before and after balancing

The results show clearly that the remaining vibrations are much less after balancing as seen in figure 7.

CONCLUSION

We have developed an algorithm that reconstructs both mass imbalances and aerodynamic imbalances arising from pitch angle errors in the rotor of a wind turbine. It is in this regards, this paper dealt with the mathematical determination of aerodynamic imbalances from pitch angle deviation of the blades and mass imbalances of the rotor. The mathematical approach has provided a reconstruction method that is implemented into a condition monitoring system. The method requires the knowledge of geometrical and physical parameters of the wind turbine and aerodynamic airfoil data of the blades. Through this approach we have recommended a Bereket Enerji's wind turbine model of SINOVEL SL1500/82-1.5MW that provided us with the system mass and stiffness matrix. In addition, we have calculated the load vector that arises in the presence of imbalances using the blade element momentum method. We have solved the vibration equation that connects the vibrations of the system and the load explicitly. The results obtained during this investigation are encouraging since the initial guess for the mass imbalance is good enough.

Both mass imbalance and aerodynamic imbalance generated lateral vibrations of the nacelle. The mass imbalance was eliminated by attaching balancing weights to the rotor; this was not possible for aerodynamic imbalances because the magnitude of aerodynamic imbalance strongly depends on the wind speed that has higher effect on torsional vibrations than mass imbalance. That's why any attempt to nullify aerodynamic imbalance by counterweights couldn't be helpful at all, that's the reason why it was compulsory to find the actual cause of nacelle vibrations in order to select the appropriate technical measures. We finally confirm that the aerodynamic imbalances do not only excite nacelle vibrations but also increase wear and damage of vital components, reduce component lifetime, increase repair costs, reduce power output to a dangerous level and reduce profit.

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Author Biblography

Eric Nduwayezu, Engineer received the B.Sc. degree in electrical engineering from Kigali Institute of Science and Technology, avenue de l' armeé Kigali, Rwanda, in 2012, and the M.Sc. degree in electrical engineering still from Sakarya University, Sakarya, Turkey, in 2015.

His research interests include renewable energy systems, electrical power systems and its protections, and detection of imbalances in wind turbine generators.

Dr. Mehmet Bayrak received the M.sc. degree in Electrical Engineering from Istanbul Technical University in 1993 and Ph.D from Istanbul Technical university in 2000. From 2009 to 2011 he served as the assistant of dean of faculty of engineering at sakarya university where he is currently the Associate Professor at the Department of Electrical and Electronics Engineering at the university of Sakarya, Turkey