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Condition monitoring of a rotor arrangement in particular a wind turbine

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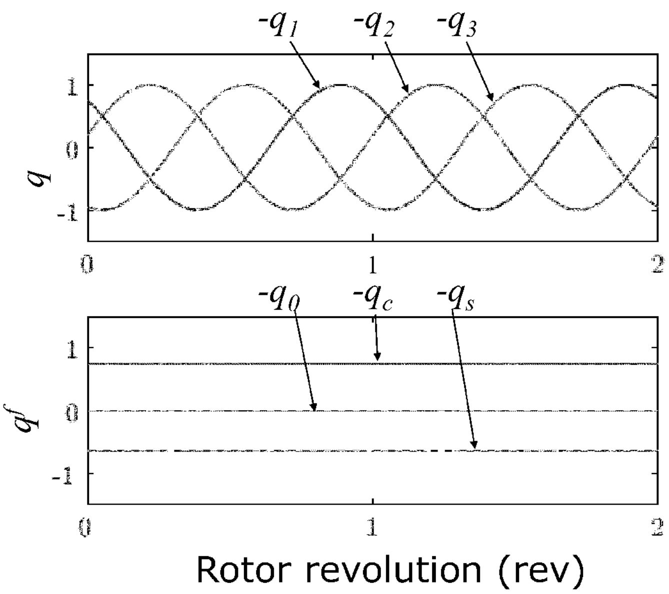

Fig. 3

(57) Abstract: The present invention relates to a method of determining the condition of a device comprising a rotor arrangement. The rotor arrangement comprising a rotational shaft and a number rotor blades each connected at the root to the rotational shaft and extending radially from the rotational shaft. Sensors are arranged to measure for each rotor blade corresponding values of one or more of the following parameters: azimuth angle (Φ) (or a parameter related to the azimuth angle), root bending moment(s) (q), such as the edgewise and/or flapwise root bending moments. The method comprises, while the rotor arrangement rotates, recording corresponding values of azimuth angle and edgewise and flap wise root bending moments for a plurality of rotations of rotor arrangement, transforming by use of e.g. a multi blade coordinate transformation, a Park's transformation or similar transformation the recorded edgewise and flap wise root bending moments (q) into a coordinate system rotating with the rotational shaft, thereby obtaining transformed root bending moments (q^f). The method further comprising identifying periodicity in each of the transformed root bending moments, determining the condition of the rotor arrangement to be faulty, in case the one or more periodicities are identified in the transformed root bending moments.

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CONDITION MONITORING OF A ROTOR ARRANGEMENT IN PARTICULAR A WIND TURBINE

FIELD OF THE INVENTION

The present invention relates to a method of determining the condition of a device comprising a rotor arrangement. The rotor arrangement comprising a rotational shaft and a number rotor blades each connected at the root to the rotational shaft and extending radially from the rotational shaft.

Sensors are arranged to measure for each rotor blade corresponding values of one or more of the following parameters: azimuth angle (Φ) (or a parameter related to the azimuth angle), root bending moment(s) (q), such as the edgewise and/or flapwise root bending moments; or parameters/measurements related to the root bending moments, such as paramaters/measurements provided by e.g. piezoelctrical sensors, strain gauge sensor or the like.

The method comprises, preferably while the rotor arrangement rotates, recording corresponding values of azimuth angle and edgewise and flap wise root bending moments for a plurality of rotations of rotor arrangement, transforming by use of e.g. a multi blade coordinate (MBC) transformation, a Park's transformation or similar transformation the recorded edgewise and flap wise root bending moments (q) into a coordinate system rotating with the rotational shaft, thereby obtaining transformed root bending moments (q^f). The method further comprising identifying periodicity in each of the transformed root bending moments and/or identify time wise growth in said transformed root bending moments, determining the condition of the rotor arrangement to be faulty, in case that one or more periodicities are identified in the transformed root bending moments and/or if a time wise growth is identified in said transformed root bending moments.

BACKGROUND OF THE INVENTION

Systems used today for diagnostic e.g. whether a wind turbine is in faulty state resides in the use of a mathematical model and/or empirical model describing the physics and dynamics of a wind turbine and limits which monitored parameter(s) should be within.

A conventional monitoring system or fault diagnosis scheme is based on a mathematical modelling of the physics and dynamics of the wind turbine. If only the main dynamics is considered then the wind turbine can be modelled by:

$$\frac{d}{dt}\left(\frac{1}{2}J\omega_r^2\right) = \frac{1}{2}\rho A\, v^3 C_p(\lambda,\beta\,) - \,T_g N\omega_r$$

This is a power equation for a wind turbine. The basic operation of a wind turbine involves adjusting the pitch β of the blades and the generator reaction torque T_g such that the produced power (first term on the right-hand side) is maximized. This optimization should be done such that the produced power and the rotor speed ω_r are kept within certain ranges. Here, ρ is the density of air, J_r is the inertia of the rotor, drive train and generator, A is the area swept by the rotor, N is the gear ratio, and $C_p(\lambda,\beta)$ is the power efficiency which depends on the pitch angles and tip speed ratio $\lambda = R\omega_r/v$. The quantities R and v are the radius of the rotor and the wind speed, respectively.

This model (and more detailed models) requires reasonable precise knowledge about all constants in the equation. In conventional "model based fault diagnoses method" this model is utilized to produce a diagnosis signal, which in the fault free case has certain statistical properties. A dection of a fault can then be based on a test whatever these properties are present. In "model based fault diagnosis methods", the diagnosis is often known as a residual signal. One standard method to obtain a residual signal is by applying an observer that is based on a detailed model.

Further, "model based diagnostic methods" are in general not capable of detecting something the model is not designed to detect and isolate. This gives a potential risk for having undetected faults in the system or detecting and isolating others faults than having occurred in the system.

In "model free fault diagnosis methods", the detection signals are derived without using a mathematical model. These methods are the so-called data-driven methods. While such methods are useful, they require information about what observed data should be when the device monitored is operating in a state defined to be non-faulty in order to detect faults as a discrepancy between observed data and non-faulty data. While this may be a workable solution, such methods suffer from the inherent problem that non-faulty data should be calculated, measured and/or estimated for all possible working conditions of the device, which in many instances are impractical or even misleading. Further, additional information is required for fault isolation. A unique change or signature from each different faults in the observed data compared with the non-faulty situation are needed to be able to isolate the faults from each other. Information about such unique changes or signatures in the observed data needs to be calculated or estimated from information about the behaviour of the system. The information can also be gathered from observed data from the system in operation over a longer period of time. This requires that all faults that need to be isolated in future operation of the system have also occurred in the observed data used for reference data. It can be a very time consuming and costly process to collect enough data to be able to describe unique changes or signatures in the observed data from each different fault. Hence, an improved method for determining the condition of a rotor arrangement would be advantageous.

OBJECT OF THE INVENTION

It is a further object of the present invention to provide an alternative to the prior art.

In particular, it may be seen as an object of the present invention to provide a method that solves the above mentioned problems of the prior art.

SUMMARY OF THE INVENTION

Thus, the above described object and several other objects are intended to be obtained in a first aspect of the invention by providing a method implemented on a computer of determining the condition of a device comprising a rotor arrangement. The rotor arrangement preferably comprises

- a rotational shaft and a number rotor blades each connected at the root to the rotational shaft and extending radially from the rotational shaft
- sensors arranged to measure for each rotor blade corresponding values of
    - azimuth angle or a parameter related to the azimuth angle

- root bending moment(s) or parameters related to the root bending moments, such as paramaters/measurements provided by e.g. piezoelctrical sensors, strain gauge sensor or the like.

The moments sensed are preferably sensed and recorded at two different, such as orthogonal, directions. Parameters related to the root bending moments may be considered –but not limited to - as signals containing signatures originating from faults.

The method preferably comprises preferably while the rotor arrangement rotates:

- recording corresponding values of azimuth angle and root bending moment(s) for a plurality of rotations of rotor arrangement,
- transforming by use of a multi blade coordinate transformation the recorded root bending moments into a coordinate system rotating with the rotational shaft, thereby obtaining transformed root bending moments,
- identifying periodicity in each of the transformed root bending moments and/or identify time wise growth pattern in said transformed root bending moments,
- determining the condition of the rotor arrangement to be faulty, in case one or more periodicities are identified in the transformed root bending moments and/or if a time wise growth is identified in the transformed root bending moments.

Thus, as presented herein, methods according to the present invention does not use a mathematical modelling of the physics and/or dynamics of the wind turbine, such as for instance a power equation for wind turbine and a method according to the invention can therefore be labelled a model-less method in which the physics of the wind turbine is not modelled by one or more modelling equations. In contrast hereto, the invention resides inter alia in the inventive finding that for a fault free wind turbine – or rotor arrangement in general – the root bending moments in the transformed space are constant in time.

In contrast, a method based on for instance a Kalman filter or an observer is directly based on and resides in determining a **residual** between the mathematical modelling of the physics of the system and observations in the physical wind turbine (that is a residual between what is predicted by the model and the real observation) is used to determine a fault. Thus, compared to this, the present invention does not determine such residuals but works on the basis of transformed root bending moments with no comparison/residual determined from a mathematical modelling of the physics of the system.

One of the advantages obtainable by the present invention may be viewed as graduation of level of information derivable about rotor arrangement. Typically, methods according to the present invention may derive information within the following graduations:

1. detect a fault in the rotor arrangement
2. isolate the detected fault to its physical position; that is typically the blade, actuator and/or sensor producing the faulty signal
3. estimate a fault and the magnitude thereof.

and be used in, typically, any load situation of the rotor arrangement.

Preferably, the invention described herein

- is a method for condition monitoring, detection and isolation faults related to the rotor part of a wind turbine,
- is only based on measuring the rotor speed and the root bending moments of the three blades,
- does not require a model of the system, and/or
- does not require knowledge of the applied controller as well as it does not use the control signals.

Further,

- sensor faults, actuator faults and faults (parametric faults) on the blades can be detected,
- faults related to the different blades can be isolated, and/or
- faults on the single blade (sensor, actuator and blade faults) can be isolated.

The invention, preferably,

- gives a measure/estimate of the fault level (fault estimation),
- can be combined with statistical tests as e.g. CUSUM test, use of neural networks, and/or
- can handle some asymmetrical from production, can compensate for it, and also give a measure of the asymmetry.

The invention might also be based on other types of transformations than the suggested MBC transformation.

It is envisaged that the invention is applicable for other type of rotating systems than wind turbine rotors, such as be applicable for three phase high voltage systems.

It is noted, and as disclosed herein, the method determines a condition of the rotor arrangements. Whether condition is to considered to be as a fault typically depends on an applied criterion as to when something is considered a fault (e.g. not operating as designed – see below). Thus, on an overall level, the invention can be seen capable of detect, isolate and/or estimate a change in the rotor system. Further, the fault may be of a character requiring immediate shut-down of the rotor or super vision. To this, the isolation of the detected fault and/or estimation of the magnitude of the fault may be very useful.
The different faults identifiable by the present invention can be dirt or ice deposited on one or more blade, mechanical failure e.g. due to breakage of mechanical components, lack of response from control devices e.g. error in pitch mechanism, as long as the fault(s) result in asymmetry in the rotor system.

In a further aspect, the invention relates to a computer program product being adapted to enable a computer system comprising at least one computer having data storage means in connection therewith to control an apparatus according to the first aspect of the invention.

In the present context a number of terms are used in a manner being ordinary to a skilled person. Some of these terms are explained as follows:

Identifying as used e.g. in identifying periodicity in each of said transformed root bending moments preferably refer to analyzing the transformed root bending momemts to detect the presence of such periodicity.

Time wise growth is preferably used to mean that the magnitude increases over time.

Growth pattern as used herein preferably refers to “fingerprints” as e.g. illustrated in figures 10-13.

Modulation/Modulating is typically used to refer to to extract a signature signal in a measured signal. This can e.g. be to extract harmonic components from measurements of root bending moments.

Faulty as in “faulty system” is used to indicate a state which operates in a different mode than intended to by control and/or operation. A wind turbine system is, e.g. considered faulty when a sensor, actuators fails i.e. not deliver the intended measurement or control actuation. A fault can also be a parametric fault resulting from a change in the system as such.

Condition is used to indicate whether a fault in the rotor arrangement has occurred or not. A fault may typically be an additive perturbation (fault), an multiplicative perturbation (fault) or a combination thereof. For illustrative purpose, consider a sensor:

$$y=a*x+b$$

where y is the measurement and x the value of interest. In a fault free situation a=1 and b=0. If a differs from 1 this is considered to be a multiplicative fault and if b is different from zero it is considered to be an additive fault. A parametric fault is characterized by a change in the system parameter and away from the nominal values.

When the rotor arrangement is faulty, the rotation of the rotor arrangement introduce a natural excitation of the system due to asymmetric loads. This excitation will results in constant values in the MBC transformation applied in the present invention, such as in the Coleman transformation or the Park’s transformation. The fault described above will induce specific signature in MBC transformation which is detectable.

Multi Blade Coordinate transformation, MBC transformation, is used to reference a transformation such as the Colemann transformation and the Park's transformation, transforming quantities recorded in fixed coordinate system into a coordinate system rotating with the rotor arrangement as disclosed herein.

Rotor arrangement is typically used to mean a device having a rotational shaft and a number rotor blades, such as 2, 3, 4 or more blades, each connected at the root to the rotational shaft and extending radially from the rotational shaft. Within the scope of rotor arrangements is considered, wind turbine rotors, helicopter rotors, turbo machinery, and a rotor arrangement with the tip of the blades arranged on a rim. Within the concept of a rotor arrangement is also considered, a rotor of a generator or electrical motor.

Blade is typically used to indicate an aerodynamic shape such as a wing.

Periodicity, such as 1p and 2p (see page below), is used to indicate a signal which repeats its values in regular intervals or periods.

This aspect of the invention is particularly, but not exclusively, advantageous in that the present invention may be accomplished by a computer program product enabling a computer system to carry out the operations of the method according to the first aspect of the invention when down- or uploaded into the computer system. Such a computer program product may be provided on any kind of computer readable medium, or through a network.

Preferably, the condition of the rotor arrangement may be determined to be suffering from an additive perturbation fault if one of the transformed root bending moments are constant in time and the remaining transformed root bending moments are periodic with a periodicity of one per revolution.

Preferably, the condition of the rotor arrangement may be determined to be suffering from a multiplicative perturbation fault if one or the transformed root bending moments is periodic with a periodicity of one per revolution and the remaining transformed root bending moments are periodic with a periodicity of two per revolution.

Preferably, the condition of the rotor arrangement may be determined to be suffering from additive and multiplicative perturbation faults if one of the transformed root bending moments is periodic with a periodicity of one per revolution and the remaining transformed root bending moments each is superposition of a transformed moment being periodic with a periodicity of one per revolution and a transformed moments being periodic with a periodicity of two per revolution.

Preferably, the multi blade coordinate transformation may be a Colemann transformation.

Preferably, the multi blade coordinate transformation may be a Park's transformation.

Preferably, the method may comprises or may further comprise, modulating the transformed moment/signals to obtain a measure for the time wise growth of transformed moments, the modulation includes a time wise integration of the transformed moments.

Preferably, each of the transformed moments may be decomposed in two directions for each signature, the directions preferably being orthogonal, such as in the directions $\cos(\Omega t)$,$\sin(\Omega t)$ and $\cos(2\Omega t)$, $\sin(2\Omega t)$, respectively, where Ω is the rotational speed of the rotor arrangement, and wherein the time wise integration is carried out on the each of the decomposed transformed moments.

Preferably, the rotor arrangement may be considered to be faulty in case the magnitude of one or more of the time wise integrated decomposed transformed moment is above a pre-selected threshold.

Preferably, the rotor arrangement may be a rotor of a windturbine.

Preferably, the root bending moments may respectively be the edgewise and the flapwise root bending moment.

Preferably the root bending moments may respectively be the in-rotor-plane and the out-of-rotor-plane moment.

Preferably, the identifying periodicity, may identify 1*p* and/or 2*p* periodicites by use an average technique based on a FFT analysis, statistical test or neural networks.

In a second aspect the invention relates to a windturbine comprising a rotor arrangement and computer means configured to carry out a method according to the first aspect.

Further aspects and embodiments are presented below as well in the accompanying claims.

The individual aspects of the present invention may each be combined with any of the other aspects. These and other aspects of the invention will be apparent from the following description with reference to the described embodiments.

BRIEF DESCRIPTION OF THE FIGURES

The present invention and in particular preferred embodiments thereof will now be described in more detail with reference to the accompanying figures. The figures show ways of implementing the present invention and is not to be construed as being limiting to other possible embodiments falling within the scope of the attached claim set.

Figure 1A is a schematic illustration of a wind turbine with effects of tower side-to-side movement and tower fore-aft movements illustrated,

Figure 1B is a schematic illustration of a wind turbine with indications of flapwise moments and edgewise moments,

Figure 1C is a schematic illustration of the azimuth angle for a rotor arrangement

Figure 2 is a schematic illustration of method of determining the condition of a rotor arrangement,

Figure 3 is a schematic illustration of the data analysis part of a method of determining the condition of a rotor arrangement,

Figure 4 is a graph showing the progression of the moments in the non-transformed space and in the transformed space,

Figure 5 illustrates in three graphs, the progression of moments in the non-transformed space, the three graphs show, additive perturbation (upper graph), multiplicative perturbation (middle graph) and multiplicative and additive perturbation (lower graph),

Figure 6 illustrates in three graphs two sets of directions (in each graph) for additive faults, and

Figure 7 illustrate in three graphs two sets of directions (in each graph) for multiplicative faults.

Figure 8 illustrates in a graph edgewise root bending moments for one blade with a 2% mass imbalance,

Figure 9 illustrates in three graphs the transformed moments q^f for the situation disclosed in fig.8,

Figures 10-13 illustrates in graphs, fingerprints, for different types of faults. The plots contains both the fault free case and the faulty situation. Figure 10 show the resulting coordinates (C_1, S_1) (see page 11) for one additive sensor fault on blade one. The plots shows the results for 1p in the first line and for 2p in the second line. In the fault free case (C_1, S_1) remains close to the Origin in all 6 plots.

Figure 11 is equivalent to Figure 10. Here is shown 4 simulations (one fault free and 3 separate additive sensor faults on each the 3 blades).

Figure 12 shows the 1p results for a mass imbalance in blade 1. The first line shows (C_1,S_1) related to the edgewise moments, while the second line shows the flap wise (C_1,S_1). Figure 13 is equivalent to Figure 12 just showing the 2p effect.

Figure 14 details the concept of flapwise and edgewise moments

Figure 15 details the concept of in-plane and out-plane bending moments.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The results presented herein are obtained by a mathematical modelling being a simulation with a high fidality software (FAST, developed by NREL, USA) of a wind turbine in order to show test results in a controllable scenario. The test results are obtained by exposing the wind turbine to wind conditions reflecting a real situation and a mass imbalance of 2 % is applied to one of the blade of the wind turbine, being a three bladed wind turbine. The moments are determined at the root of the blade and are therefore in the following referred to a root bending moments – or in short – just moments. It is emphasized, that the mass imbalance of 2% is one among many other scenarios the invention can operate in and the results presented below are not be construed as limiting to the scope of the invention.

Reference is made to fig. 1 which illustrates schematically the six bending moments considered in the test described above; that is three blade edgewise bending moments and three blade flapwise bending moments. Accordingly, for each blade a blade edgewise bending moment (q_e) and a blade flapwise bending moment (q_f) are determined (or in-plane and out-of-plane moments are determined).

Reference is made to fig. 2 which schematically illustrates methods according to the present invention of determining the condition of a rotor arrangement on an overall level. It is noted with reference to the fig. 2, the diagnosis is also to be considered as an general feature and typically takes as input a condition provided by the data analysis. The diagnosis step may comprise one or more of the steps of detect, isolate and/or estimate a fault and if desired its magnitude.

As presented in fig. 2, data analysis methods according to the present invention are based on a multiblade coordinate transformation, MBC, and the thereby obtained transformed moments are analyzed in order to determine the condition of the rotor arrangement. As indicated in fig. 2, two different strategies may applied in order to the determine condition of the rotor arrangement based on the transformed moments, namely:

- analyzing the transformed moments to identify 1*p (basic the rotational frequency)* and/or 2*p* (double rotational frequency) signals in the transformed moments, which may be used to detect, isolate and/or estimate fault or change;
- modulation of the transformed moments to identify time wise growth patterns in the transformed moments.

It is noted that while the fig. 2 suggest that the step of "Analysing for 1*p* and/or 2*p* signals" is a step before the step of "Modulation of transformed moments to identify time wise growth patterns", it is often preferred to perform the modulation step before the analyzing step. For instance, in preferred embodiments, e.g. an integration e.g. as presented in equation (I) below is made and an examination for fault is made. Thereafter an analysis with respect to 1*p* and/or 2*p* signals is made to isolate the fault(s).

As presented herein, the analyzing step of identify 1*p* and/or 2*p* signals in the transformed moments may in certain embodiments of the invention be a method to determine the condition of the windturbine (or a rotor arrangement in general), while the modulation step may be seen as a further step thereto in a method of determining the condition of a windturbine (or a rotor arrangement in general). This is illustrated schematically in fig. 2 as the two steps labelled "Analyzing…" and "Modulation …" are arranged in series. In this connection, the analyzing step of identify 1*p* and/or 2*p* signals can be carried out by a FFT analysis, statistical test, neural networks or similar methods.

As further presented herein, the identification of 1*p* and/or 2*p* signals may be used to identify the condition of the windturbine, while the modulation step may provide more detailed information of the cause of e.g. a faulty condition and in some instances also provide information about which part of the rotor arrangement being in a faulty and normal condition (normal condition is considered to be a situation where no fault is determined).

It is noted that although specific embodiments refer to moments and transformed moment, the input to the methods according present invention is signals, such as electrical signals, and thereby other physical quantities can be used instead of or in combination with the moments.

In a first embodiment of the invention, the MBC transformation is Coleman transformation which is applied in the following manner. The root bending moments are considered to be periodic and depend on the azimuth angle,$\Phi(t)$, see fig. 2 (or the corresponding value, rotor speed) and the Colemann transformation is applied on the two sets of root bending moments, $q_{i,e,f}$ wherein index i refers to the blade number, "e" refers to edgewise and "f" refers to flapwise), to provide transformed root bending moments, q^f in the following manner (for rotor with three blades):

$$q^{e,f} = \begin{bmatrix} q_0^{e,f} \\ q_c^{e,f} \\ q_s^{e,f} \end{bmatrix} = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{2}{3}\cos(\Phi_1(t)) & \frac{2}{3}\cos(\Phi_2(t)) & \frac{2}{3}\cos(\Phi_3(t)) \\ \frac{2}{3}\sin(\Phi_1(t)) & \frac{2}{3}\sin(\Phi_2(t)) & \frac{2}{3}\sin(\Phi_3(t)) \end{bmatrix} \cdot \begin{bmatrix} q_{1,e,f} \\ q_{2,e,f} \\ q_{3,e,f} \end{bmatrix}$$

Where q is the measured root bending moments and q^f is the transformed root bending moments. The notation used in the above with respect to subscript on q means that for instance $q_{1,e,f}$ has to independent components namely $(q_{1,e}; q_{1,f})$ where $q_{1,e}$ is the edgewise component and $q_{1,f}$ is the flap wise component. It is further noted that the edgewise and flapwise components are used indepently in the above transformation so that $q^{e,f}$ is calculated edgewise and flapwise giving in total two vectors each having three components. Thus,

$$q^e = \begin{pmatrix} q_0^e \\ q_c^e \\ q_s^e \end{pmatrix} \qquad q^f = \begin{pmatrix} q_0^f \\ q_c^f \\ q_s^f \end{pmatrix}$$

While the Colemann transformation is considered to be a feature of a preferred embodiment, other MBC transformation can be used, such as the Park's transformation disclosed below.

In a second embodiment, the MBC transformation is a Park's transformation and following the above, the Park's transformation is applied on the two sets of root bending moments, q, to provide transformed root bending moments, q^f, in the following manner:

$$\hat{q}^{e,f} = \begin{bmatrix} \hat{q}_0^{e,f} \\ \hat{q}_c^{e,f} \\ \hat{q}_s^{e,f} \end{bmatrix} = \begin{bmatrix} \frac{2}{3}\cos(\Phi_1(t)) & \frac{2}{3}\cos(\Phi_2(t)) & \frac{2}{3}\cos(\Phi_3(t)) \\ -\frac{2}{3}\sin(\Phi_1(t)) & -\frac{2}{3}\sin(\Phi_2(t)) & -\frac{2}{3}\sin(\Phi_3(t)) \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix} \cdot \begin{bmatrix} q_{1,e,f} \\ q_{2,e,f} \\ q_{3,e,f} \end{bmatrix}$$

Where the notation $\hat{q}$ is used to indicate that the Park's transformation is used.

The outputs of the MBC (or Park's) transformation are constant if the rotor system is symmetrical or fault free. This is disclosed in fig. 4, for a rotor with three blades.

The upper graph of fig. 4 shows the measured root bending moments for each of the three blades as function of rotor revolution (rev). The moments q_1,q_2,and q_3 are unspecified with respect to edgewise or flapwise as the general progression for the edgewise and the flapwise moments are similar to each other. As shown in the upper part of fig. 4, the moments are periodic and as shown in the lower part of fig. 4 (the transformed moments), the transformed moments are constant, when no perturbation is present.

In a faulty system, the transformed root bending moments (by use of the Coleman transformation disclosed above) will include 1p signals and 2p signals in the following manner:

	q_0^f	q_c^f	q_s^f
Additive fault	Constant signal	$1p$ signal	$1p$ signal
Multiplicative fault	$1p$ signal	$2p$ signal	$2p$ signal
Additive and Multiplicative fault	$1p$ signal	Superposition of a $1p$ signal and a $2p$ signal	Superposition of a $1p$ signal and a $2p$ signal

Where 1p refers to a signal being periodic within one rotation of the rotor and 2p refers to a signal being periodic with a double rotation of the rotor.

This is shown in fig. 5 in three graphs. The upper graph illustrate the case of an additive perturbation and it is clear from the graph that q_0^f is constant and that q_c^f and q_s^f is a signal with a one-per-revolution periodicity (1p signal).

The middle graph of fig 5 illustrates the case of an multiplicative perturbation and it is clear from the graph that q_0^f, q_c^f and q_s^f each is a signal with a one-per-revolution periodicity (1p signal) – it is noted that the three signals in the transformed space are out-of-phase.

The lower part of fig. 5 illustrated the case of both a multiplicative and additive perturbation. While the results for the isolated additive and multiplicative perturbation appeared strictly periodic, the result in fig. 5 may be viewed as a superpositioning of the additive and multiplicative results.

As shown in the upper graph of fig. 4, the moments are periodic in the non-transformed space, whereas they are constant in the transformed space, when no fault is present. Thus, by applying a multiblade coordinate transformation, MBC, on the moments and analysing the transformed moments to identify, if present, $1p$ and/or $2p$ signals therein, the condition of the rotor arrangement can be determined.

While the condition can be determined by analysing for $1p$ and $2p$ signals, the source for a fault can be difficult to establish from the transformed moments alone. In order to identify the source of a fault a modulation of the transformed moments may be applied according to the invention.

On analysing the output from the MBC transformation

The following is further elaborated in the proceeding section labelled "Further details on MBC transformation". Although the method of determining the condition of a rotor arrangement by identifying 1p- and 2p-variations in the transformed moments provides useful results, the following provides an efficient way to determining the condition by analysing the output from the MBC transformation.

In general, a fault can be detected by multiplying the output from the MBC transformation by cos (Ωt) and sin(Ωt) and evaluating the fault signature δ_i as:

$$\delta_i = \int_0^t \sqrt{((q_i^f \cos(\Omega t))^2 + (q_i^f \sin(\Omega t))^2)}dt \quad i=1,\ldots,6 \qquad \text{(I)}$$

where index i refers to one of the (six) components determined by the MBC transformation and Ω is the rotational speed (frequency) of the rotor. Thus, if a fault is present, this typically shows up in the above signature δ_i as a time wise growth (increasing function over time).

The connection between the angular rotor speed Ω(t) and the azimuth angle $\phi(t)$ is as follows:

$$\dot{\phi}(t) = \Omega(t)$$

The angular rotor speed Ω(t) is not constant. Therefore the angular rotor speed Ω(t) and/or the azimuth angle $\phi(t)$ should be measured and filtered to reduce the effect of the noise.

In practical implementation of the method, the integral is e.g. evaluated in a discrete manner for instance as:

$$\delta_i = \sum_{t=0}^{t=T} ((q_i^f \cos(\Omega t))^2 + (q_i^f \sin(\Omega t))^2)\Delta t$$

Where *t=0* is selected to be the point in time where the evaluation is started and *T* is the point in time where δ_i is considered. As inherent in the method, *t=0* and *t=T* can be selected arbitrarily; and the discrete time interval *Δt* can also be selected arbitrarily. However, these selections should preferably be made so as to minimise the discretization error.

If δ_i is an increasing function of t, then q_i^f include a 1p components which indicate that the rotor system is not symmetrical any more due to a fault. In the same way, 2p components can be detected (Ω->2 Ω).

The present invention further provide the advantageous feature of isolating a fault to a specific blade. This can be provided in the following manner. The two terms in the above integration can be considered separately:

$$C_i = \int_0^t q_i^f \cos(\Omega t) dt \quad i=1,\ldots,6$$

$$S_i = \int_0^t q_i^f \sin(\Omega t) dt \quad i=1,\ldots,6$$

where C_i and S_i can be viewed as a coordinate set (C_i,S_i) in the complex plane. As shown, the modulation involves an integration over time of each of the transformed moments decomposed in the orthogonal directions:

cos(Ωt) and sin(Ωt).

Reviewing these coordinate sets, it is noted that the directions in the complex plane are directly related to the single blades and this is used according to the present invention to provide an isolation of a fault into which blade the fault is related to. In a practical implementation the integrals are calculated using a discretization:

$$C_i = \sum_{t=0}^{t=T} q_i^f \cos(\Omega t)\,\Delta t \quad i = 1,\ldots,6$$

$$S_i = \sum_{t=0}^{t=T} q_i^f \sin(\Omega t)\,\Delta t \quad i = 1,\ldots,6$$

Similarly, the same considerations apply for a signal with 2p components.

Thus, for a windturbine with three blades and two moments measured per blade, the following coordinates may be determined:

$$[(C_1,S_1)\ldots(C_6,S_6)]$$

With respect to modulation of 1p signals. Similary, the same set of coordinates are obtained with respect to modulation of 2p signal given by:

$$C_i = \int_0^t q_i^f \cos(2\Omega t)dt \quad i=1,\ldots,6$$
$$S_i = \int_0^t q_i^f \sin(2\Omega t)dt \quad i=1,\ldots,6$$

As these coordinates are evaluated from *t=0* to *t=T* the coordinates will have their timewise starting points in (0,0) and as the integrals will be increasing or decreasing functions in time (depending on the signs of *q*)) the coordinates will divert away from (0,0) in a direction depending on *q.* It is noted, that although the fault free situation should produce the coordinates (0,0) being constant in time, the sensors may produce noisy signals which may result in that the coordinates deviated slightly from (0,0). This may typically be dealt with in the present invention by defining a threshold. Statistical test such as to GLR test (generalized likelihood test) or CUSUM test (cumulative sum test) have shown to be useful in connection with the present invention for that purpose. However, other statistical tests may be applied.

As noted above, the time=0 in the numerical integration may be selected arbitrary as even if the method of determining a condition of a rotor arrangement is initiated at a condition being faulty, the fault will show-up either as a 1*p*, 2*p* signal as an increasing function in the modulation.

As noise in many systems may be present in the system, the 1*p*, the 2*p* signals and the increasing function in the modulation are preferably selected to be the result of a faulty system when exceeding a pre-determined magnitude threshold.

As indicated above, isolation of a fault to a specific blade may be carried out according to the present invention. In order to accomplish this in a smooth manner, the invention make use of phase information in the following manner.

Following the above calculations (see also section labelled Further details on MBC transformation below), it can be derived that for an <u>additive fault</u> (of size δ_a) on blade 1, 2 and 3 respectively the following directions can be determined:

Additive fault on blade 1 yield the following constant part in the transformation and modulation:

$$\begin{bmatrix}\begin{pmatrix}q_c^f\cos(\Omega t)\\ q_c^f\sin(\Omega t)\end{pmatrix}\\ \begin{pmatrix}q_s^f\cos(\Omega t)\\ q_s^f\sin(\Omega t)\end{pmatrix}\end{bmatrix}_{const} = \frac{1}{3}\delta_a\begin{bmatrix}\begin{pmatrix}\cos(\Phi_0)\\ -\sin(\Phi_0)\end{pmatrix}\\ \begin{pmatrix}\sin(\Phi_0)\\ \cos(\Phi_0)\end{pmatrix}\end{bmatrix}$$

wherein index "*const*" means constant part in the transformation and modulation.

Similarly, an additive fault on blade 2 yield the following constant part in the transformation and modulation:

$$\begin{bmatrix}\begin{pmatrix}q_c^f\cos(\Omega t)\\ q_c^f\sin(\Omega t)\end{pmatrix}\\ \begin{pmatrix}q_s^f\cos(\Omega t)\\ q_s^f\sin(\Omega t)\end{pmatrix}\end{bmatrix}_{const} = \frac{1}{3}\delta_a\begin{bmatrix}\begin{pmatrix}\cos(-\frac{2}{3}\pi+\Phi_0)\\ -\sin(-\frac{2}{3}\pi+\Phi_0)\end{pmatrix}\\ \begin{pmatrix}\sin(-\frac{2}{3}\pi+\Phi_0)\\ \cos(-\frac{2}{3}\pi+\Phi_0)\end{pmatrix}\end{bmatrix}$$

And, an additive fault on blade 3 yield the following constant part in the transformation and modulation:

$$\begin{bmatrix}\begin{pmatrix}q_c^f\cos(\Omega t)\\ q_c^f\sin(\Omega t)\end{pmatrix}\\ \begin{pmatrix}q_s^f\cos(\Omega t)\\ q_s^f\sin(\Omega t)\end{pmatrix}\end{bmatrix}_{const} = \frac{1}{3}\delta_a\begin{bmatrix}\begin{pmatrix}\cos(-\frac{4}{3}\pi+\Phi_0)\\ -\sin(-\frac{4}{3}\pi+\Phi_0)\end{pmatrix}\\ \begin{pmatrix}\sin(-\frac{4}{3}\pi+\Phi_0)\\ \cos(-\frac{4}{3}\pi+\Phi_0)\end{pmatrix}\end{bmatrix}$$

Reviewing the above equation, δ_a can be identified as a measure for the *magnitude* of the fault and the elements in brackets [..] on which δ_a is multiplied can be viewed as a direction for the fault in case the equations are viewed as a vector representation (having a length and direction) of the fault.

Thus, from the above equations, two directions are provided for each blade. For blade 1, e.g., we get:

$$\begin{bmatrix}\begin{pmatrix}x_c\\y_c\end{pmatrix}\\\begin{pmatrix}x_s\\y_s\end{pmatrix}\end{bmatrix}=\begin{bmatrix}\begin{pmatrix}q_c^f\cos(\Omega t)\\q_c^f\sin(\Omega t)\end{pmatrix}\\\begin{pmatrix}q_s^f\cos(\Omega t)\\q_s^f\sin(\Omega t)\end{pmatrix}\end{bmatrix}_{const}=\frac{1}{3}\delta_a\begin{bmatrix}\begin{pmatrix}\cos(\Phi_0)\\-\sin(\Phi_0)\end{pmatrix}\\\begin{pmatrix}\sin(\Phi_0)\\\cos(\Phi_0)\end{pmatrix}\end{bmatrix}$$

which can be plot against each other as shown in fig. 6. As shown in these figures, each of the orientations of the directions $(\cos(\Phi_0), -\sin(\Phi_0))$ and $(\sin(\Phi_0), \cos(\Phi_0))$ are uniquely linked to one of the blades and as δ_a is different from zero (or close to zero) orientations can be used as a fingerprint of which blade the additive fault appears at.

For the case of <u>multiplicative</u> fault (of size δ_m) on each blade, similar to the above applies and the equations providing the directions have the following form:

For a multiplicative fault on blade 1:

$$\begin{bmatrix}\begin{pmatrix}x_0\\y_0\end{pmatrix}\\\begin{pmatrix}x_c\\y_c\end{pmatrix}\\\begin{pmatrix}x_s\\y_s\end{pmatrix}\end{bmatrix}=\begin{bmatrix}\begin{pmatrix}q_o^f\cos(\Omega t)\\q_o^f\sin(\Omega t)\end{pmatrix}\\\begin{pmatrix}q_c^f\cos(2\Omega t)\\q_c^f\sin(2\Omega t)\end{pmatrix}\\\begin{pmatrix}q_s^f\cos(2\Omega t)\\q_s^f\sin(2\Omega t)\end{pmatrix}\end{bmatrix}_{const}=\frac{1}{6}\delta_m\begin{bmatrix}\begin{pmatrix}0\\1\end{pmatrix}\\\begin{pmatrix}\sin(\Phi_0)\\\cos(\Phi_0)\end{pmatrix}\\\begin{pmatrix}\cos(\Phi_0)\\-\sin(\Phi_0)\end{pmatrix}\end{bmatrix}$$

For a multiplicative fault on blade 2:

$$\begin{bmatrix}\begin{pmatrix}x_0\\y_0\end{pmatrix}\\\begin{pmatrix}x_c\\y_c\end{pmatrix}\\\begin{pmatrix}x_s\\y_s\end{pmatrix}\end{bmatrix}=\begin{bmatrix}\begin{pmatrix}q_o^f\cos(\Omega t)\\q_o^f\sin(\Omega t)\end{pmatrix}\\\begin{pmatrix}q_c^f\cos(2\Omega t)\\q_c^f\sin(2\Omega t)\end{pmatrix}\\\begin{pmatrix}q_s^f\cos(2\Omega t)\\q_s^f\sin(2\Omega t)\end{pmatrix}\end{bmatrix}_{const}=\frac{1}{6}\delta_m\begin{bmatrix}\begin{pmatrix}-\frac{\sqrt{3}}{2}\\-\frac{1}{2}\end{pmatrix}\\\begin{pmatrix}\sin(-\frac{4}{3}\pi+\Phi_0)\\\cos(-\frac{4}{3}\pi+\Phi_0)\end{pmatrix}\\\begin{pmatrix}\cos(-\frac{4}{3}\pi+\Phi_0)\\-\sin(-\frac{4}{3}\pi+\Phi_0)\end{pmatrix}\end{bmatrix}$$

And, for a multiplicative fault on blade 3:

$$\begin{bmatrix} \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} \\ \begin{pmatrix} x_c \\ y_c \end{pmatrix} \\ \begin{pmatrix} x_s \\ y_s \end{pmatrix} \end{bmatrix} = \begin{bmatrix} \begin{pmatrix} q_o^f \cos(\Omega t) \\ q_o^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_c^f \cos(2\Omega t) \\ q_c^f \sin(2\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(2\Omega t) \\ q_s^f \sin(2\Omega t) \end{pmatrix} \end{bmatrix}_{const} = \frac{1}{6}\delta_m \begin{bmatrix} \begin{pmatrix} -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} \end{pmatrix} \\ \begin{pmatrix} \sin(-\frac{2}{3}\pi + \Phi_0) \\ \cos(-\frac{2}{3}\pi + \Phi_0) \end{pmatrix} \\ \begin{pmatrix} \cos(-\frac{2}{3}\pi + \Phi_0) \\ -\sin(-\frac{2}{3}\pi + \Phi_0) \end{pmatrix} \end{bmatrix}$$

These directions are plotted in fig. 7 and it is seen as for the additive fault that the plots are fingerprints unique for a specific blade.

Thus, by reviewing these sets of equation (and with reference to figures), it can be seen that the blade having the fault can be isolated.

In the following, an example of the above will be disclosed. Fig. 8 illustrates an example of an edgewise blade root bending moment for one blade with a 2 % mass imbalance. Fig. 9 illustrates in three graphs the moments (for the situation of fig. 8) transformed by use of the Coleman transformation. In fig. 9 legends Coleman signal 1, 2 and 3 refer respectively to q_0,q_f, q_s.

By applying the above, the results can be illustrated as presented in the following figures 10-13:

Figures 10-13 illustrates in graphs, fingerprints, for different types of faults. The plots contains both the fault free case and the faulty situation. Figure 10 show the resulting coordinates (C_1, S_1) (see page 11) for one additive sensor fault on blade one. The plots shows the results for 1p in the first line and for 2p in the second line. In the fault free case (C_1, S_1) remains close to the Origin in all 6 plots.

Figure 11 is equivalent to Figure 10. Here is shown 4 simulations (one fault free and 3 separate additive sensor faults on each the 3 blades).

Figure 12 shows the 1p results for a mass imbalance in blade 1. The first line shows (C_1,S_1) related to the edgewise moments, while the second line shows the flap wise (C_1,S_1). Figure 13 is equivalent to Figure 12 just showing the 2p effect.

In these figures, the legends “mean”, “tilt” and “yaw” refers to the Coleman signals q_0, q_f, q_c respectively.

As it appears from these figures, a fault in one of the blade and the nature of the fault provides a unique fingerprint which can be used to detect, isolate and estimate the nature of the fault and to which blade (and sensor, in case one or more sensors fail) it is associated.

The invention can be implemented by means of hardware, software, firmware or any combination of these. The invention or some of the features thereof can also be implemented as software running on one or more data processors and/or digital signal processors.

The individual elements of an embodiment of the invention may be physically, functionally and logically implemented in any suitable way such as in a single unit, in a plurality of units or as part of separate functional units. The invention may be implemented in a single unit, or be both physically and functionally distributed between different units and processors.

Reference is made to fig. 14 detailing the concept of flapwise and edgewise moments and to fig. 15 detailing the concept of in-plane and out-plane bending moments. The rotational movement of the blades defines a plane in space. The direction parallel to the drive train is orthogonal to this plane. If the pitch angle of one blade is known/measured then simple trigonometric relations can be used to transform the measurements of the root bending moments. The measured root bending moments in edge and flap wise direction can be transformed into root bending moments in the rotational plane (in plane root bending moments) and in the direction parallel to the drive train (out of plane root bending moments).

The description of the invention has been focussed on edgewise and flapwise root bending moments. However, and as illustrated in fig. 14 and 15, moments evaluated in other directions such as "out of rotor plane" and "in rotor plane" moments can be used in relation to the present invention. In such situation, the moments (say for blade 1) $q_{1,e}$ is replaced with for instance the in-plane moment and $q_{1,f}$ is replaced with for instance the out-of-plane moment in above formulae.

As presented herein, the invention typically provides a fingerprint of the fault. In order to identify an recorded fingerprint to a specific fault, the invention make comprise a database storing various fingerprints with related information on which fault is generating the fingerprint. Then, when an actual fingerprint is obtained, this fingerprint may be compared to what it stored in the database and if a match is found, the information related to the fingerprint can be retrieved to provide an identification of the fault.

A match is typically considered to have been found if the orientations in the fingerprints compared are similar to each other.

FURTHER DETAILS ON MBC TRANSFORMATION

A. Multi Blade Coordinate Transformation

The multi-blade coordinate (MBC) transformation is described in the following. The MBC transformation is a central element in the detection and isolation of faults in the rotor part of the wind turbine. First the fundamentals in the MBC transformation is given following by a state space description of the MBC transformation.

B. The MBC Transformation Fundamentals

The MBC Transformation enables the transformation from a rotating frame of reference to a fixed frame of reference. The azimuth angle $\Phi_i(t)$ of each blade $i = 1, \dots, n_b$, assuming constant rotor speed Ω and equal angular spacing between the blades, is given by

$$\Phi_i(t) = \Phi_0 + \Omega t - (i-1)2\pi/n_b, \qquad i = 1, \dots n_b \tag{1}$$

and renders the MBC transformation a function of time t rather than the azimuth angle $\Phi_i(t)$. Φ_0 is the angle between the angles applied in the MBC transformation and the rotor blades. For a 3-blades rotor, the azimuth angles can be combined in a vector, which is $\Phi(t) = [\Phi_1(t)\ \Phi_2(t)\ \Phi_3(t)]^T$. The temporal argument of states and transformation matrices in the following has been omitted to simplify notation. The rotating frame coordinates q and the fixed frame coordinates q^f have the following relationship

$$q^f = \boldsymbol{M}q \qquad q = \boldsymbol{M}^{-1}q^f \qquad q^f = [q_0\ q_c\ q_s]^T \tag{2}$$

where the MBC transformation matrices are

$$\boldsymbol{M} = \begin{bmatrix} \frac{1}{3}1^T \\ \frac{2}{3}\cos\Phi^T(t) \\ \frac{2}{3}\sin\Phi^T(t) \end{bmatrix}, \qquad \boldsymbol{M}^{-1} = \begin{bmatrix} 1^T \\ \cos\Phi(t)^T \\ \sin\Phi(t)^T \end{bmatrix}^T, \tag{3}$$

and $1 = [1\ 1\ 1]^T$, $cos\Phi(t) = [cos\Phi_1(t)\ \ cos\Phi_2(t)\ \ cos\Phi_3(t)\ ]^T$ and similar for $sin(\Phi(t))$.

$$q = \boldsymbol{M}^{-1} q^{f} \qquad (4a)$$

$$q = \dot{\boldsymbol{M}}^{-1} q^{f} + \boldsymbol{M}^{-1} \dot{q}^{f} \qquad (4b)$$

$$\ddot{q} = \ddot{\boldsymbol{M}}^{-1} q^{f} + 2\dot{\boldsymbol{M}}^{-1} \dot{q}^{f} + \boldsymbol{M}^{-1} \ddot{q}^{f} \qquad (4c)$$

where (4a) is the base transformation and (4b) is derived from $\dot{q} = \frac{d}{dt}\left(\boldsymbol{M}^{-1} q^{f}\right)$ and (4c) from $\ddot{q} = \frac{d}{dt}\left(\dot{\boldsymbol{M}}^{-1} q^{f} + \boldsymbol{M}^{-1} \dot{q}^{f}\right)$. Here:

$$\dot{\boldsymbol{M}}^{-1} = \Omega \begin{bmatrix} 0^{T} \\ -\sin \Phi(t)^{T} \\ \cos \Phi(t)^{T} \end{bmatrix}^{T} \quad and \quad \ddot{\boldsymbol{M}}^{-1} = \Omega^{2} \begin{bmatrix} 0^{T} \\ -\cos \Phi(t)^{T} \\ -\sin \Phi(t)^{T} \end{bmatrix}^{T}$$

The inverse transformations are given by

$$q^f = \boldsymbol{M}q \tag{5a}$$

$$\dot{q}^f = \frac{2}{3}\dot{\boldsymbol{M}}^{-T}q + \boldsymbol{M}\dot{q} \tag{5b}$$

$$\ddot{q}^f = \frac{2}{3}\ddot{\boldsymbol{M}}^{-T}q + \frac{4}{3}\dot{\boldsymbol{M}}^{-T}\dot{q} + \boldsymbol{M}\ddot{q} \tag{5c}$$

C. The MBC transformation applied on a state space model

A dynamic system in state space form can be expressed by a nonlinear ordinary differential equation vector function and a vector output function as

$$\dot{x}(t) = f(x(t), u(t), t) \tag{6a}$$

$$y(t) = g(x(t), u(t), t) \tag{6b}$$

where states x, inputs u, outputs y and the vector functions f and g are all functions of time. In the following, the temporal arguments of states, inputs and outputs and vector functions have been omitted to simplify notation.

First order Taylor expansion around the linearization $(\bar{x}, \bar{u})$ yields

$$\dot{x} = f(\bar{x}, \bar{u}) + \boldsymbol{A}(x - \bar{x}) + \boldsymbol{B}(u - \bar{u}) \tag{7a}$$

$$y = g(\bar{x}, \bar{u}) + \boldsymbol{C}(x - \bar{x}) + \boldsymbol{D}(u - \bar{u}) \tag{7b}$$

where the system matrices $(\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}, \boldsymbol{D})$ are functions of time. The linearization can be rewritten to

$$\dot{x} = \boldsymbol{A}x + \boldsymbol{B}u + \delta, \qquad \delta = f(\bar{x}, \bar{u}) - \boldsymbol{A}\bar{x} - \boldsymbol{B}\bar{u} \tag{8a}$$

$$y = \boldsymbol{C}x + \boldsymbol{D}u + \gamma, \qquad \gamma = g(\bar{x}, \bar{u}) - \boldsymbol{C}\bar{x} - \boldsymbol{D}\bar{u} \tag{8b}$$

for typical linear control theory the pair $(\bar{x}, \bar{u})$ is chosen to be an equilibrium point (such that $0 = f(\bar{x}, \bar{u})$), but the theory is also valid for other choices of $(\bar{x}, \bar{u})$.

The time-varying rotating frame system can be transformed to a fixed frame time-invariant system where the states, inputs and outputs are transformed to the fixed frame of reference

$$x^f = \boldsymbol{M_x}\, x$$
$$u^f = \boldsymbol{M_u}\, u$$
$$y^f = \boldsymbol{M_y}\, y$$

The MBC transformations gives the fixed frame system equations

$$\dot{x}^f = \boldsymbol{A^f} x^f + \boldsymbol{B^f} u^f + \delta^f \qquad (9a)$$
$$y^f = \boldsymbol{C^f} x^f + \boldsymbol{D^f} u^f + \gamma^f \qquad (9b)$$

where

$$A^f = \widetilde{M}_x\left(AM_x^{-1} - \dot{M}_x^{-1}\right), \qquad C^f = M_y C M_x^{-1},$$
$$B^f = \widetilde{M}_x B M_u^{-1}, \qquad D^f = M_y D M_u^{-1},$$
$$\delta^f = \widetilde{M}_x \delta, \qquad \gamma^f = M_y \gamma$$

The system matrices (A^f,B^f,C^f,D^f) are time-invariant, as are the offset vectors (δ^f,γ^f) when rotating frame variables have been averaged in the linearisation point.

D. MBC for Systems with Asymmetries

The MBC transformation for an isotropic rotor will result in time-invariant quantities, i.e. the time-varying azimuth angles $\Phi_i(t)$ will be transformed into constant angles in the fixed frame. This is based on the condition that inputs to the transformation are symmetric. When this condition is not satisfied, the azimuth angels in the fixed frame will not be constant. This is analyzed in more details in the following.

Let the periodic input vector q be given by:

$$q = \begin{bmatrix} \sin(\Phi_1(t) - \Phi_0) \\ \sin(\Phi_2(t) - \Phi_0) \\ \sin(\Phi_3(t) - \Phi_0) \end{bmatrix} \qquad (10)$$

where $\Phi_i(t)$ is given by (1). Further, the MBC transformation matrix M be given by (3). In the fixed frame, q^f in (2) is given by:

$$q^f = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{2}{3}\cos(\Phi_1(t)) & \frac{2}{3}\cos(\Phi_2(t)) & \frac{2}{3}\cos(\Phi_3(t)) \\ \frac{2}{3}\sin(\Phi_1(t)) & \frac{2}{3}\sin(\Phi_2(t)) & \frac{2}{3}\sin(\Phi_3(t)) \end{bmatrix} q \qquad (11)$$

$$= \begin{bmatrix} 0 \\ -\sin(\Phi_0) \\ \cos(\Phi_0) \end{bmatrix}$$

It can be seen from (11) that the MBC transformation in the nominal case gives constant states in the fixed frame.

Introducing two types of perturbations at q, an additive perturbation δ_a and a multiplicative perturbation δ_m. First, let's consider the case of including an additive perturbation to q. Let the perturbation q be given by:

$$q = \begin{bmatrix} \sin(\Phi_1(t) - \Phi_0) \\ \sin(\Phi_2(t) - \Phi_0) \\ \sin(\Phi_3(t) - \Phi_0) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \delta_a \end{bmatrix} \qquad (12)$$

i.e. a perturbation at q_3. In the fixed frame, q^f is given by:

$$q^f = \begin{bmatrix} 0 \\ -\sin(\Phi_0) \\ \cos(\Phi_0) \end{bmatrix} + \begin{bmatrix} \frac{1}{3}\delta_a \\ \frac{2}{3}\delta_a\cos(\Omega t - \frac{4}{3}\pi + \Phi_0) \\ \frac{2}{3}\delta_a\sin(\Omega t - \frac{4}{3}\pi + \Phi_0) \end{bmatrix} \quad (13)$$

From (13) we have that all components in q^f are proportional with the additive perturbation δ_a. Further, an additive perturbation gives constant q_0 and 1p-variation in q_c and q_s.

Now, let's consider the case where the input includes a multiplicative perturbation. The perturbation q is then given by:

$$q = \begin{bmatrix} \sin(\Phi_1(t) - \Phi_0) \\ \sin(\Phi_2(t) - \Phi_0) \\ (1 + \delta_m)\sin(\Phi_3(t) - \Phi_0) \end{bmatrix} = \begin{bmatrix} \sin(\Phi_1(t) - \Phi_0) \\ \sin(\Phi_2(t) - \Phi_0) \\ \sin(\Phi_3(t) - \Phi_0) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \delta_m\sin(\Phi_3(t) - \Phi_0) \end{bmatrix} \quad (14)$$

The perturbation is again placed at q_3. In the fixed frame, q^f is given by:

$$q^f = \begin{bmatrix} 0 \\ -\sin(\Phi_0) \\ \cos(\Phi_0) \end{bmatrix} + \begin{bmatrix} \frac{1}{3}\delta_m \sin(\Phi_3(t) - \Phi_0) \\ \frac{2}{3}\delta_m \cos(\Phi_3(t))\sin(\Phi_3(t) - \Phi_0) \\ \frac{2}{3}\delta_m \sin(\Phi_3(t))\sin(\Phi_3(t) - \Phi_0) \end{bmatrix} \quad (15)$$

$$= \begin{bmatrix} \frac{1}{3}\delta_m \sin(\Omega t - \frac{4}{3}\pi) \\ -(1 + \frac{1}{3}\delta_m)\sin(\Phi_0) + \frac{1}{3}\delta_m \sin(2\Omega t - \frac{2}{3}\pi + \Phi_0) \\ (1 + \frac{1}{3}\delta_m)\cos(\Phi_0) + \frac{1}{3}\delta_m \cos(2\Omega t - \frac{2}{3}\pi + \Phi_0) \end{bmatrix}$$

From (15) we have again that all components in $q^f$are proportional with the multiplicative perturbation δ_m. Further, it gives a 1p-variation of q_0 and a 2p-variationin q_c and q_s. At last, note that is also a phase shift between the input and the outputs in q_c and q_s.

The results for various perturbations are shown in Figures 4 og 5.

A multiplicative perturbation is shown in Figure 5, gives a 1p-variation in q_0 and a 2p-variation in q_c and q_s.

Faults on the rotor part of the wind turbine will in general result in asymmetries in the rotor. Using the MBC transformation, it will be possible to detect for asymmetries in the rotor which is an indirect detection of faults in the system. This is the basic for the fault detection and also fault isolation in the rotor system as it will be shown in the following.

The above two types of perturbation are the standard faults/perturbation considered in connection with fault diagnosis. However, in connection with the MBC transformation, it is also relevant to consider phase perturbation, i.e. there is a phase perturbation in one of the input signals.

In the general MBC transformation, it is also possible to consider the case where a phase perturbation is included. This is included for completeness, but is not so relevant in connection with faults on wind turbines.

Let a phase perturbation q be given by:

$$q = \begin{bmatrix} \sin(\Phi_1(t) - \Phi_0) \\ \sin(\Phi_2(t) - \Phi_0) \\ \sin\left(\Phi_3(t) - \Phi_0 - \Phi_{f,3}\right) \end{bmatrix}$$

$$= \begin{bmatrix} \sin(\Phi_1(t) - \Phi_0) \\ \sin(\Phi_2(t) - \Phi_0) \\ \sin(\Phi_3(t) - \Phi_0) + (\sin\left(\Phi_3(t) - \Phi_0 - \Phi_{f,3}\right) - \sin(\Phi_3(t) - \Phi_0)) \end{bmatrix}$$

$$= \begin{bmatrix} \sin(\Omega t) \\ \sin(\Omega t - \frac{2}{3}\pi) \\ \sin\left(\Omega t - \frac{4}{3}\pi\right) - 2\cos(\Omega t - \frac{4}{3}\pi - \frac{1}{2}\Phi_{f,3})\sin(\frac{1}{2}\Phi_{f,3}) \end{bmatrix} \quad (16)$$

i.e. a perturbation at q_3. In the fixed frame, q^f is given by:

$$q^f = \begin{bmatrix} 0 \\ -\sin(\Phi_0) \\ \cos(\Phi_0) \end{bmatrix} + \begin{bmatrix} -\frac{2}{3}\sin\left(\frac{1}{2}\Phi_{f,3}\right)\cos\left(\Omega t - \frac{4}{3}\pi - \frac{1}{2}\Phi_{f,3}\right) \\ -\frac{2}{3}\sin\left(\frac{1}{2}\Phi_{f,3}\right)\cos\left(\Phi_0 i + \frac{1}{2}\Phi_{f,3}\right) - \frac{2}{3}\sin\left(\frac{1}{2}\Phi_{f,3}\right)\cos\left(2\Omega t + \Phi_0 - \frac{2}{3}\pi - \frac{1}{2}\Phi_{f,3}\right) \\ -\frac{2}{3}\sin\left(\frac{1}{2}\Phi_{f,3}\right)\sin\left(\Phi_0 + \frac{1}{2}\Phi_{f,3}\right) - \frac{2}{3}\sin\left(\frac{1}{2}\Phi_{f,3}\right)\sin\left(2\Omega t + \Phi_0 - \frac{2}{3}\pi - \frac{1}{2}\Phi_{f,3}\right) \end{bmatrix} \quad (17)$$

$$= \begin{bmatrix} 0 \\ -\sin(\Phi_0) - \frac{2}{3}\sin\left(\frac{1}{2}\Phi_{f,3}\right)\cos\left(\Phi_0 + \frac{1}{2}\Phi_{f,3}\right) \\ \cos(\Phi_0) - \frac{2}{3}\sin\left(\frac{1}{2}\Phi_{f,3}\right)\sin\left(\Phi_0 + \frac{1}{2}\Phi_{f,3}\right) \end{bmatrix} + \begin{bmatrix} -\frac{2}{3}\sin(\frac{1}{2}\Phi_{f,3})\cos(\Omega t - \frac{4}{3}\pi - \frac{1}{2}\Phi_{f,3}) \\ -\frac{2}{3}\sin\left(\frac{1}{2}\Phi_{f,3}\right)\cos(2\Omega t + \Phi_0 - \frac{2}{3}\pi - \frac{1}{2}\Phi_{f,3}) \\ -\frac{2}{3}\sin\left(\frac{1}{2}\Phi_{f,3}\right)\sin(2\Omega t + \Phi_0 - \frac{2}{3}\pi - \frac{1}{2}\Phi_{f,3}) \end{bmatrix}$$

From (17), we can see that a phase perturbation gives a 1p-variation in q_0 and a 2p-variation in q_c and q_s, equivalent with the multiplicative perturbations.

E. Evaluation of time varying signals

The analysis given above show that a constant additive perturbation will result in constant perturbation of q_0 and a periodic perturbation with 1p-variation in q_c and q_s in the fixed coordinate frame. A constant multiplicative perturbation will give perturbations with both 1p and 2p-variations in the fixed frame.

For analyzing the output of the MBC transformation, a modulation of the q^f is applied with respect to the 1p-variations and the 2p-variations.

First, let's consider the additive case where q^f is given by (13). The constant term in q_0^f from the additive fault cannot be applied in connection with the following diagnosis, as it will showed later. This term will therefore not be considered further. The two terms in (13) are given by:

$$\begin{bmatrix} q_c^f \\ q_s^f \end{bmatrix} = \begin{bmatrix} \frac{2}{3}\delta_a \cos\left(\Omega t - \frac{4}{3}\pi + \Phi_0\right) \\ \frac{2}{3}\delta_a \sin\left(\Omega t - \frac{4}{3}\pi + \Phi_0\right) \end{bmatrix} \quad (18)$$

Multiplying now q_c^f and q_s^f with both $\cos(\Omega t)$ and $\sin(\Omega t)$ gives the following four signals:

$$\begin{bmatrix} \begin{pmatrix} q_c^f \cos(\Omega t) \\ q_c^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(\Omega t) \\ q_s^f \sin(\Omega t) \end{pmatrix} \end{bmatrix} = \frac{1}{3}\delta_a \begin{bmatrix} \begin{pmatrix} \cos\left(\frac{4}{3}\pi - \Phi_0\right) + \cos\left(2\Omega t - \frac{4}{3}\pi + \Phi_0\right) \\ \sin\left(\frac{4}{3}\pi - \Phi_0\right) + \sin\left(2\Omega t - \frac{4}{3}\pi + \Phi_0\right) \end{pmatrix} \\ \begin{pmatrix} \sin\left(-\frac{4}{3}\pi + \Phi_0\right) + \sin\left(2\Omega t - \frac{4}{3}\pi + \Phi_0\right) \\ \cos\left(-\frac{4}{3}\pi + \Phi_0\right) + \cos\left(2\Omega t - \frac{4}{3}\pi + \Phi_0\right) \end{pmatrix} \end{bmatrix} \quad (19)$$

The constant terms in (19) is the given by:

$$\begin{bmatrix} \begin{pmatrix} q_c^f \cos(\Omega t) \\ q_c^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(\Omega t) \\ q_s^f \sin(\Omega t) \end{pmatrix} \end{bmatrix}_{constant} = \frac{1}{3}\delta_a \begin{bmatrix} \begin{pmatrix} \cos\left(-\frac{4}{3}\pi + \Phi_0\right) \\ -\sin\left(-\frac{4}{3}\pi + \Phi_0\right) \end{pmatrix} \\ \begin{pmatrix} \sin\left(-\frac{4}{3}\pi + \Phi_0\right) \\ \cos\left(-\frac{4}{3}\pi + \Phi_0\right) \end{pmatrix} \end{bmatrix} \quad (20)$$

(20) gives two vectors in the complex plane specified by the phase $\frac{4}{3}\pi + \Phi_0$. An integration of these signals can be used for detection of an additive fault in the system. A simple detection scheme is to use:

$$\varepsilon_{detection} = \int_0^t (\sqrt{(q_c^f \cos(\Omega t))^2 + (q_c^f \sin(\Omega t))^2})\, dt \approx \frac{1}{3}\, \delta_a\, t \tag{21}$$

that will give an increasing function for an additive fault (assuming that the fault occur at $t = 0$). Also a CUSUM test method can be applied.

However, in connection with fault isolation, we need some more information. This can directly be obtained by considering the two signals involved in (21), so we also get a direction in the complex plane. The (21) take the following form:

$$\begin{bmatrix} \varepsilon_{c,real} \\ \varepsilon_{c,imag} \end{bmatrix} = \begin{bmatrix} \int_0^t q_c^f \cos(\Omega t) dt \\ \int_0^t q_c^f \sin(\Omega t) dt \end{bmatrix} \approx \frac{1}{3}\delta_a \begin{bmatrix} \cos\left(-\frac{4}{3}\pi + \Phi_0\right) \\ -\sin\left(-\frac{4}{3}\pi + \Phi_0\right) \end{bmatrix} t \tag{22}$$

(again assumed that the fault had occurred at $t = 0$).

This give a direction in the complex plane depending of the phase $\frac{4}{3}\pi + \Phi_0$. Now we can do the same by using q_s^f. This will give a direction that is orthogonal on the calculated direction in (22).

The above calculation has been done for a fault on the last input (blade no. 3) to the MBC transformation. Redo the above calculations, we get the following directions for the three inputs (blades).

An additive fault on input no. 1 gives:

$$\begin{bmatrix} \begin{pmatrix} q_c^f \cos(\Omega t) \\ q_c^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(\Omega t) \\ q_s^f \sin(\Omega t) \end{pmatrix} \end{bmatrix}_{1,constant} = \frac{1}{3}\delta_a \begin{bmatrix} \begin{pmatrix} \cos(\Phi_0) \\ -\sin(\Phi_0) \end{pmatrix} \\ \begin{pmatrix} \sin(\Phi_0) \\ \cos(\Phi_0) \end{pmatrix} \end{bmatrix} \quad (23)$$

An additive fault on input no. 2 gives:

$$\begin{bmatrix} \begin{pmatrix} q_c^f \cos(\Omega t) \\ q_c^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(\Omega t) \\ q_s^f \sin(\Omega t) \end{pmatrix} \end{bmatrix}_{2,constant} = \frac{1}{3}\delta_a \begin{bmatrix} \begin{pmatrix} \cos(-\frac{2}{3}\pi + \Phi_0) \\ -\sin(-\frac{2}{3}\pi + \Phi_0) \end{pmatrix} \\ \begin{pmatrix} \sin(-\frac{2}{3}\pi + \Phi_0) \\ \cos(-\frac{2}{3}\pi + \Phi_0) \end{pmatrix} \end{bmatrix} \quad (24)$$

An additive fault on input no. 3 gives:

$$\begin{bmatrix} \begin{pmatrix} q_c^f \cos(\Omega t) \\ q_c^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(\Omega t) \\ q_s^f \sin(\Omega t) \end{pmatrix} \end{bmatrix}_{3,constant} = \frac{1}{3}\delta_a \begin{bmatrix} \begin{pmatrix} \cos(-\frac{4}{3}\pi + \Phi_0) \\ -\sin(-\frac{4}{3}\pi + \Phi_0) \end{pmatrix} \\ \begin{pmatrix} \sin(-\frac{4}{3}\pi + \Phi_0) \\ \cos(-\frac{4}{3}\pi + \Phi_0) \end{pmatrix} \end{bmatrix} \quad (25)$$

Using the directions given by (23) – (25), it is simple to see that we can isolate which blade the fault is related to.

In the multiplicative case, all three terms in q^f result in a 1p variation or a 2p variation. From (15), the three terms related to the multiplicative faults in input no. 3 are given by:

$$\begin{bmatrix} q_0^f \\ q_c^f \\ q_s^f \end{bmatrix} = \frac{1}{3}\delta_m \begin{bmatrix} \sin(\Omega t - \frac{4}{3}\pi) \\ \sin(2\Omega t - \frac{2}{3}\pi + \Phi_0) \\ \cos(2\Omega t - \frac{2}{3}\pi + \Phi_0) \end{bmatrix} \quad (26)$$

Following the same line as in connection with additive faults, the them the first term in (26) is multiplied by $\cos(\Omega t)$ and $\sin(\Omega t)$ and the last two terms is multiplied by $\cos(2\Omega t)$ and $\sin(2\Omega t)$. This gives the following results for multiplicative faults on the three inputs:

A multiplicative fault on input no. 1 gives:

$$\begin{bmatrix} \begin{pmatrix} q_0^f \cos(\Omega t) \\ q_0^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_c^f \cos(2\Omega t) \\ q_c^f \sin(2\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(2\Omega t) \\ q_s^f \sin(2\Omega t) \end{pmatrix} \end{bmatrix}_{1,constant} = \frac{1}{6}\delta_m \begin{bmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \\ \begin{pmatrix} \sin(\Phi_0) \\ \cos(\Phi_0) \end{pmatrix} \\ \begin{pmatrix} \cos(\Phi_0) \\ -\sin(\Phi_0) \end{pmatrix} \end{bmatrix} \quad (27)$$

A multiplicative fault on input no. 2 gives:

$$\begin{bmatrix} \begin{pmatrix} q_0^f \cos(\Omega t) \\ q_0^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_c^f \cos(2\Omega t) \\ q_c^f \sin(2\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(2\Omega t) \\ q_s^f \sin(2\Omega t) \end{pmatrix} \end{bmatrix}_{2,constant} = \frac{1}{6}\delta_m \begin{bmatrix} \begin{pmatrix} -\frac{1}{2}\sqrt{3} \\ -\frac{1}{2} \end{pmatrix} \\ \begin{pmatrix} \sin\left(-\frac{4}{3}\pi + \Phi_0\right) \\ \cos\left(-\frac{4}{3}\pi + \Phi_0\right) \end{pmatrix} \\ \begin{pmatrix} \cos\left(-\frac{4}{3}\pi + \Phi_0\right) \\ -\sin\left(-\frac{4}{3}\pi + \Phi_0\right) \end{pmatrix} \end{bmatrix} \quad (28)$$

A multiplicative fault on input no. 3 gives:

$$\begin{bmatrix} \begin{pmatrix} q_0^f \cos(\Omega t) \\ q_0^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_c^f \cos(2\Omega t) \\ q_c^f \sin(2\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(2\Omega t) \\ q_s^f \sin(2\Omega t) \end{pmatrix} \end{bmatrix}_{3,constant} = \frac{1}{6}\delta_m \begin{bmatrix} \begin{pmatrix} \frac{1}{2}\sqrt{3} \\ -\frac{1}{2} \end{pmatrix} \\ \begin{pmatrix} \sin\left(-\frac{2}{3}\pi + \Phi_0\right) \\ \cos\left(-\frac{2}{3}\pi + \Phi_0\right) \end{pmatrix} \\ \begin{pmatrix} \cos\left(-\frac{2}{3}\pi + \Phi_0\right) \\ -\sin\left(-\frac{2}{3}\pi + \Phi_0\right) \end{pmatrix} \end{bmatrix} \quad (29)$$

It is again possible to isolate which input (blade) the fault is related to be based on the above results.

In the phase case, all three terms in q^f result in a 1p variation or a 2p variation. From (17), the three terms related to the phase faults in input no. 3 are given by:

$$\begin{bmatrix} q_0^f \\ q_c^f \\ q_s^f \end{bmatrix} = -\frac{2}{3}\sin(\frac{1}{2}\Phi_{f,3})\begin{bmatrix} \cos(\Omega t - \frac{4}{3}\pi - \frac{1}{2}\Phi_{f,3}) \\ \cos(2\Omega t + \Phi_0 - \frac{2}{3}\pi - \frac{1}{2}\Phi_{f,3}) \\ \sin(2\Omega t + \Phi_0 - \frac{2}{3}\pi - \frac{1}{2}\Phi_{f,3}) \end{bmatrix} \quad (30)$$

Following the same line as in connection with multiplicative faults, the them the first term in (30) is multiplied by $\cos(\Omega t)$ and $\sin(\Omega t)$ and the last two terms is multiplied by $\cos(2\Omega t)$ and $\sin(2\Omega t)$. This gives the following results for phase faults on the three inputs:

A phase fault on input no. 1 gives:

$$\begin{bmatrix} \begin{pmatrix} q_0^f \cos(\Omega t) \\ q_0^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_c^f \cos(2\Omega t) \\ q_c^f \sin(2\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(2\Omega t) \\ q_s^f \sin(2\Omega t) \end{pmatrix} \end{bmatrix}_{1,constant} = \frac{1}{3}\sin(\frac{1}{2}\Phi_{f,3}) \begin{bmatrix} \begin{pmatrix} -\cos\left(-\frac{1}{2}\Phi_{f,3}\right) \\ \sin\left(-\frac{1}{2}\Phi_{f,3}\right) \end{pmatrix} \\ \begin{pmatrix} -\cos\left(\Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \\ \sin\left(\Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \end{pmatrix} \\ \begin{pmatrix} -\sin\left(\Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \\ -\cos\left(\Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \end{pmatrix} \end{bmatrix} \quad (31)$$

A phase fault on input no. 2 gives:

$$\begin{bmatrix} \begin{pmatrix} q_0^f \cos(\Omega t) \\ q_0^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_c^f \cos(2\Omega t) \\ q_c^f \sin(2\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(2\Omega t) \\ q_s^f \sin(2\Omega t) \end{pmatrix} \end{bmatrix}_{2,constant} = \frac{1}{3}\sin(\frac{1}{2}\Phi_{f,3}) \begin{bmatrix} \begin{pmatrix} -\cos\left(-\frac{2}{3}\pi - \frac{1}{2}\Phi_{f,3}\right) \\ \sin\left(-\frac{2}{3}\pi - \frac{1}{2}\Phi_{f,3}\right) \end{pmatrix} \\ \begin{pmatrix} -\cos\left(-\frac{4}{3}\pi + \Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \\ \sin\left(-\frac{4}{3}\pi + \Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \end{pmatrix} \\ \begin{pmatrix} -\sin\left(-\frac{4}{3}\pi + \Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \\ -\cos\left(-\frac{4}{3}\pi + \Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \end{pmatrix} \end{bmatrix} \quad (32)$$

A phase fault on input no. 3 gives:

$$\begin{bmatrix} \begin{pmatrix} q_0^f \cos(\Omega t) \\ q_0^f \sin(\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_c^f \cos(2\Omega t) \\ q_c^f \sin(2\Omega t) \end{pmatrix} \\ \begin{pmatrix} q_s^f \cos(2\Omega t) \\ q_s^f \sin(2\Omega t) \end{pmatrix} \end{bmatrix}_{3,constant} = \frac{1}{3}\sin(\frac{1}{2}\Phi_{f,3}) \begin{bmatrix} \begin{pmatrix} -\cos\left(-\frac{4}{3}\pi - \frac{1}{2}\Phi_{f,3}\right) \\ \sin\left(-\frac{4}{3}\pi - \frac{1}{2}\Phi_{f,3}\right) \end{pmatrix} \\ \begin{pmatrix} -\cos\left(-\frac{2}{3}\pi + \Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \\ \sin\left(-\frac{2}{3}\pi + \Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \end{pmatrix} \\ \begin{pmatrix} -\sin\left(-\frac{2}{3}\pi + \Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \\ -\cos\left(-\frac{2}{3}\pi + \Phi_0 - \frac{1}{2}\Phi_{f,3}\right) \end{pmatrix} \end{bmatrix} \quad (33)$$

It is again possible to isolate which input (blade) the fault is related to be based on the above results.

The two sets of directions shown in (23) – (25) for additive faults and (27) – (29) for multiplicative faults are shown in Figure 6 and Figure 7, respectively.

Although the present invention has been described in connection with the specified embodiments, it should not be construed as being in any way limited to the presented examples. The scope of the present invention is to be interpreted in the light of the accompanying claim set. In the context of the claims, the terms "comprising" or "comprises" do not exclude other possible elements or steps. Also, the mentioning of references such as "a" or "an" etc. should not be construed as excluding a plurality. The use of reference signs in the claims with respect to elements indicated in the figures shall also not be construed as limiting the scope of the invention. Furthermore, individual features mentioned in different claims, may possibly be advantageously combined, and the mentioning of these features in different claims does not exclude that a combination of features is not possible and advantageous.

CLAIMS

1. A method implemented on a computer of determining the condition of a device comprising a rotor arrangement, the rotor arrangement comprising

- a rotational shaft (1) and a number rotor blades (2a, 2b, 2c) each connected at the root to the rotational shaft and extending radially from the rotational shaft
- sensors (3) arranged to measure for each rotor blade (2a, 2b, 2c) corresponding values of
  - azimuth angle (Φ) or a parameter related to the azimuth angle
  - root bending moment(s) (q) or parameters related to the root bending moments, such as paramaters/measurements/signals provided by e.g. piezoelctrical sensors, strain gauge sensor or the like ;

the method comprising, preferably while the rotor arrangement rotates:

- recording corresponding values of azimuth angle and root bending moments for a plurality of rotations of rotor arrangement,
- transforming by use of a multi blade coordinate transformation the recorded root bending moments (q) into a coordinate system rotating with the rotational shaft (1), thereby obtaining transformed root bending moments (q^f),
- identifying periodicity, if present, in each of said transformed root bending moments and/or identify time wise growth, if present, in said transformed root bending moments,
- determining the condition of the rotor arrangement to be faulty, in case one or more periodicities are identified in said transformed root bending moments and/or if a time wise growth is identified in said transformed root bending moments.

2. A method according to claim 1, wherein the condition of the rotor arrangement is determined to be suffering from an additive perturbation fault if one of the transformed root bending moments are constant in time and the remaining transformed root bending moments are periodic with a periodicity of one per revolution.

3. A method according to claim 2 or 3, wherein the condition of the rotor arrangement is determined to be suffering from a multiplicative perturbation fault if one or the transformed root bending moments is periodic with a periodicity of one per revolution and the remaining transformed root bending moments are periodic with a periodicity of two per revolution.

4. A method according to any of the preceding claims, wherein the condition of the rotor arrangement is determined to be suffering from additive and multiplicative perturbation faults if one of the transformed root bending moments is periodic with a periodicity of one per revolution and the remaining transformed root bending moments each is superposition of a transformed moment being periodic with a periodicity of one per revolution and a transformed moments being periodic with a periodicity of two per revolution.

5. A method according to any of the preceding claims, wherein the multi blade coordinate transformation is a Colemann transformation.

6. A method according to any of the preceding claims 1-4, wherein the multi blade coordinate transformation is a Park's transformation.

7. A method according to any of the preceding claims comprising or further comprising, modulating the transformed moment/signals to obtain a measure for the time wise growth of transformed moments, the modulation includes a time wise integration of the transformed moments.

8. A method according to any of the preceding claims, wherein each of the transformed moments are decomposed in two directions for each signature, the directions preferably being orthogonal, such as in the the directions $\cos(\Omega t)$,$\sin(\Omega t)$ and $\cos(2\Omega t)$, $\sin(2\Omega t)$, respectively, where Ω is the rotational speed of the rotor arrangement, and wherein the time wise integration is carried out on the each of the decomposed transformed moments.

9. A method according to claim 7 or 8, wherein the rotor arrangement is considered to be faulty in case the magnitude of one or more of the time wise integrated decomposed transformed moment is above a pre-selected threshold.

10. A method according to any of the preceding claims, where the rotor arrangement is a rotor of a windturbine.

11. A method according to any of the preceding claims, wherein the root bending moments are respectively the edgewise and the flapwise root bending moment.

12. A method according to any of the preceding claims 1-10, wherein the root bending moments are respectively the in-rotor-plane and the out-of-rotor-plane moment.

13. A method according to any of the preceding claims, wherein said identifying periodicity identify 1*p* and/or 2*p* periodicites by use an average technique based on a FFT analysis, statistical test or neural networks.

14. A windturbine comprising a rotor arrangement and computer means configured to carry out the method according to any of the preceding claims.

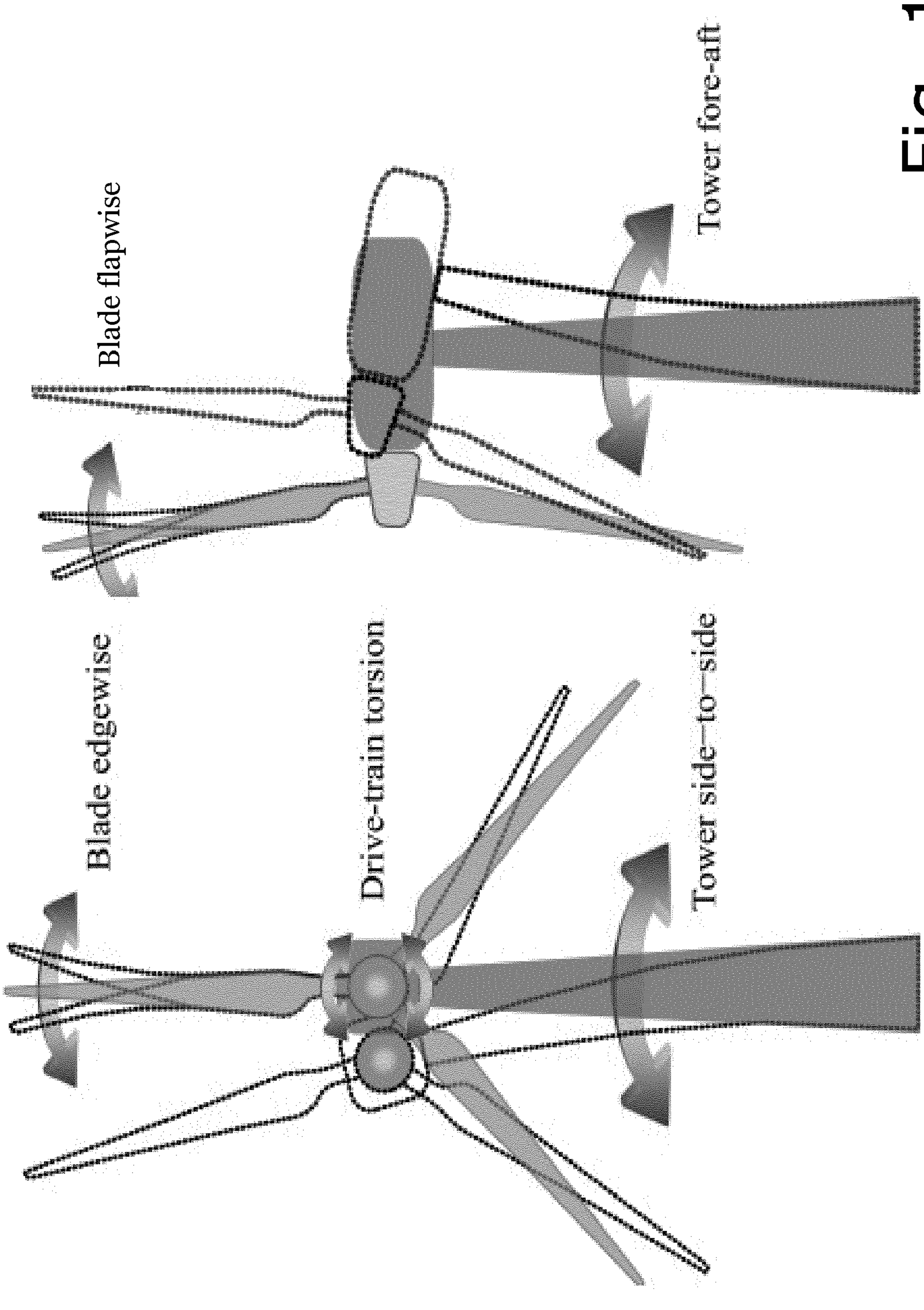

Blade flapwise
Tower fore-aft
Blade edgewise
Drive-train torsion
Tower side–to–side

Fig. 1A

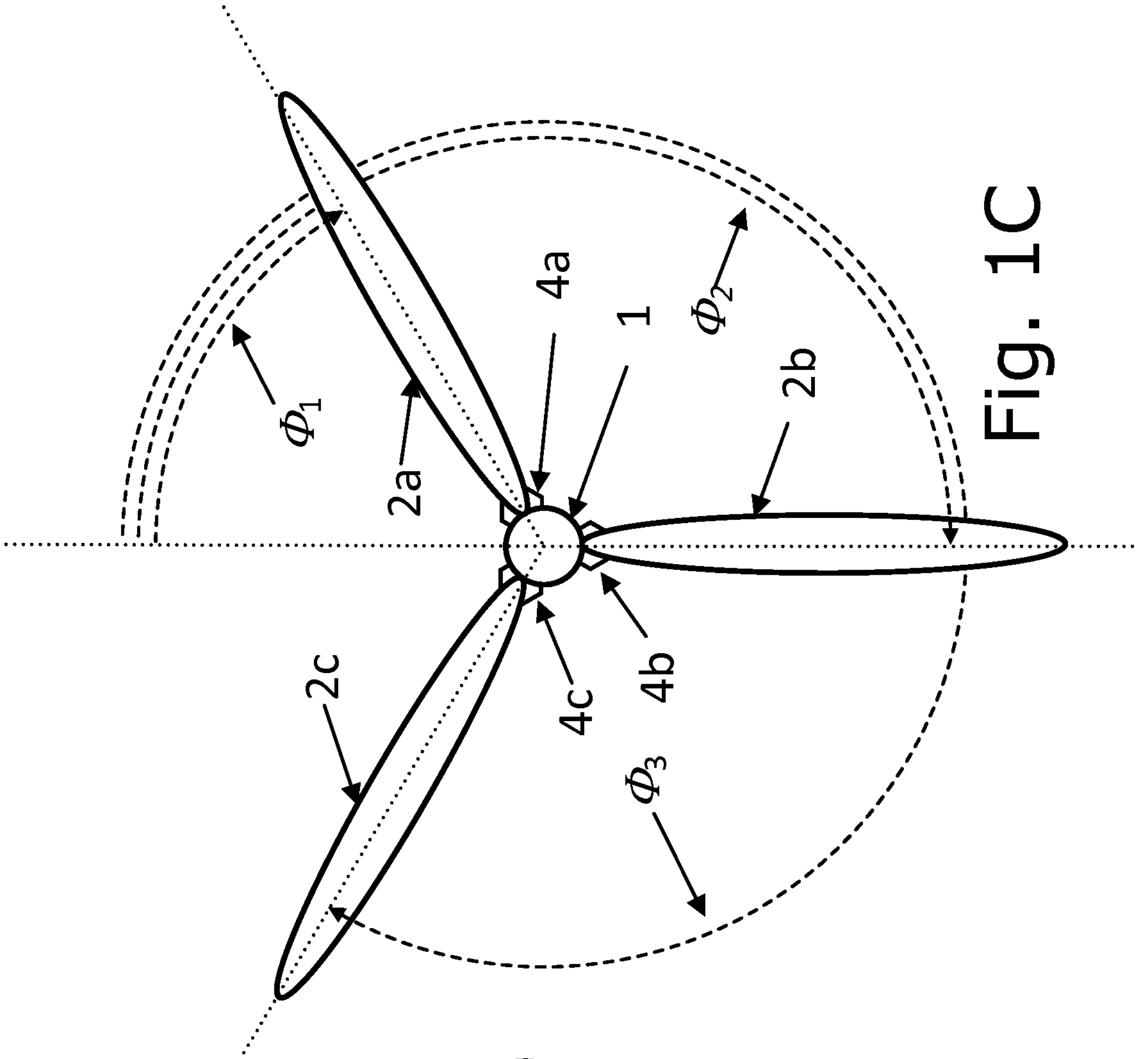

2a
4a
1
Φ_1
Φ_2
2b
2c
4c
4b
Φ_3

Fig. 1C

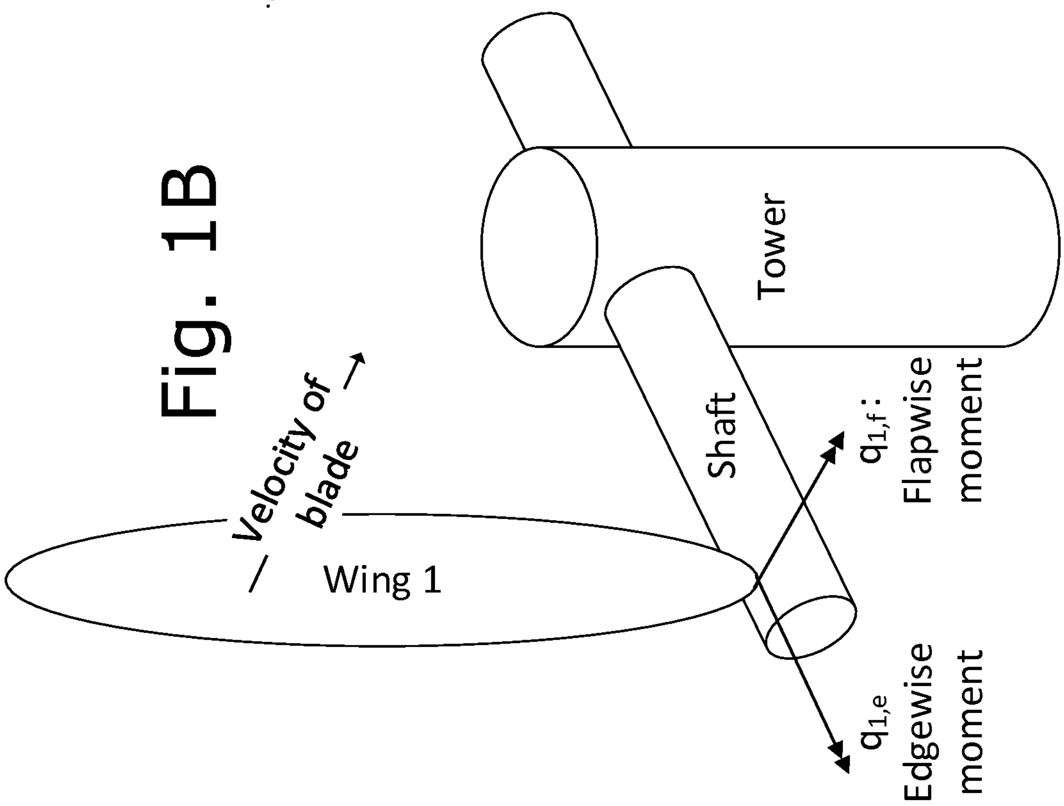

Tower
Shaft
Wing 1
Velocity of blade
$q_{1,f}$: Flapwise moment
$q_{1,e}$ Edgewise moment

Fig. 1B

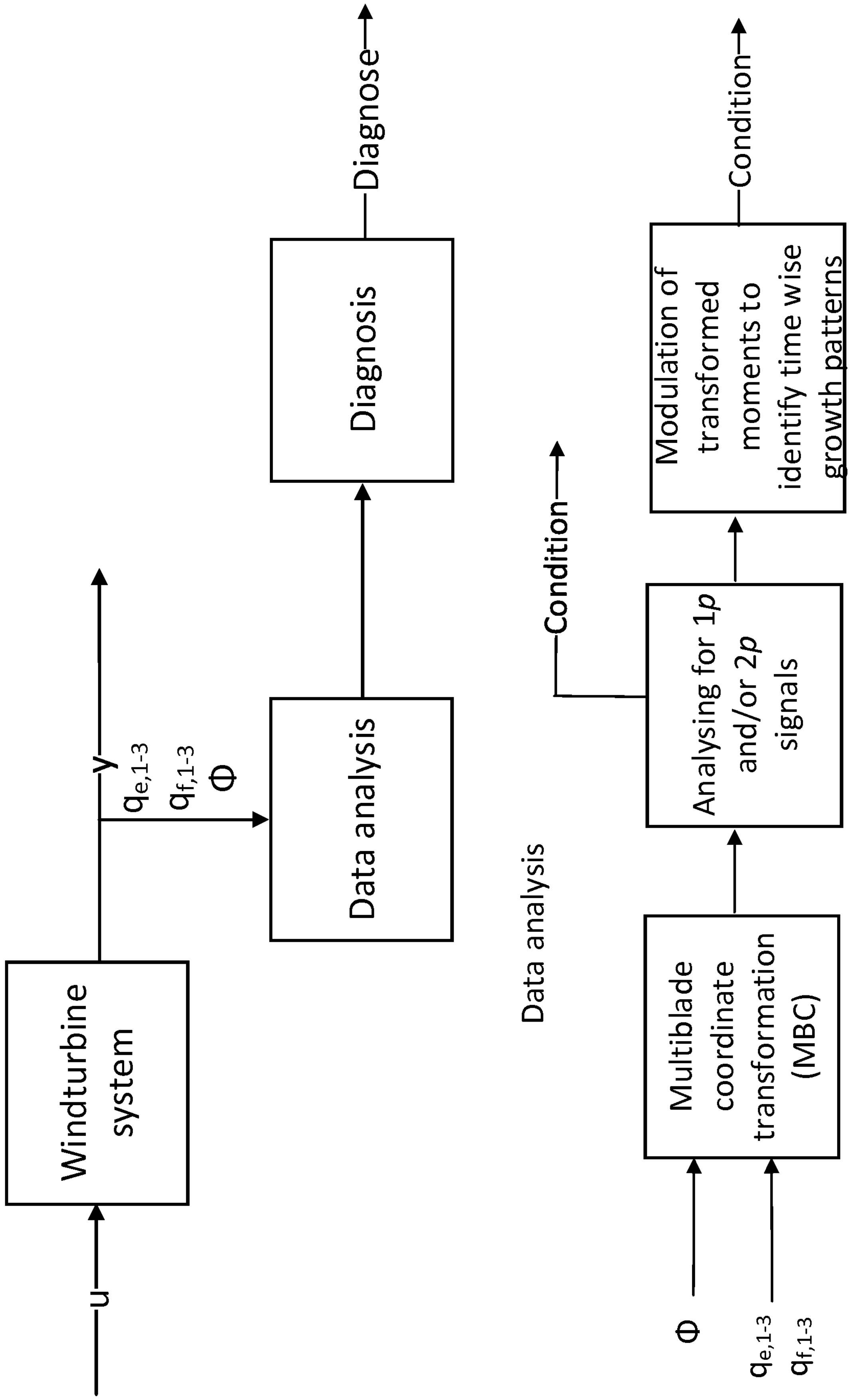

u
Windturbine system
y
qe,1-3
qf,1-3
Φ
Data analysis
Diagnosis
Diagnose
Data analysis
Φ
qe,1-3
qf,1-3
Multiblade coordinate transformation (MBC)
Analysing for 1p and/or 2p signals
Condition
Modulation of transformed moments to identify time wise growth patterns
Condition

Fig. 2

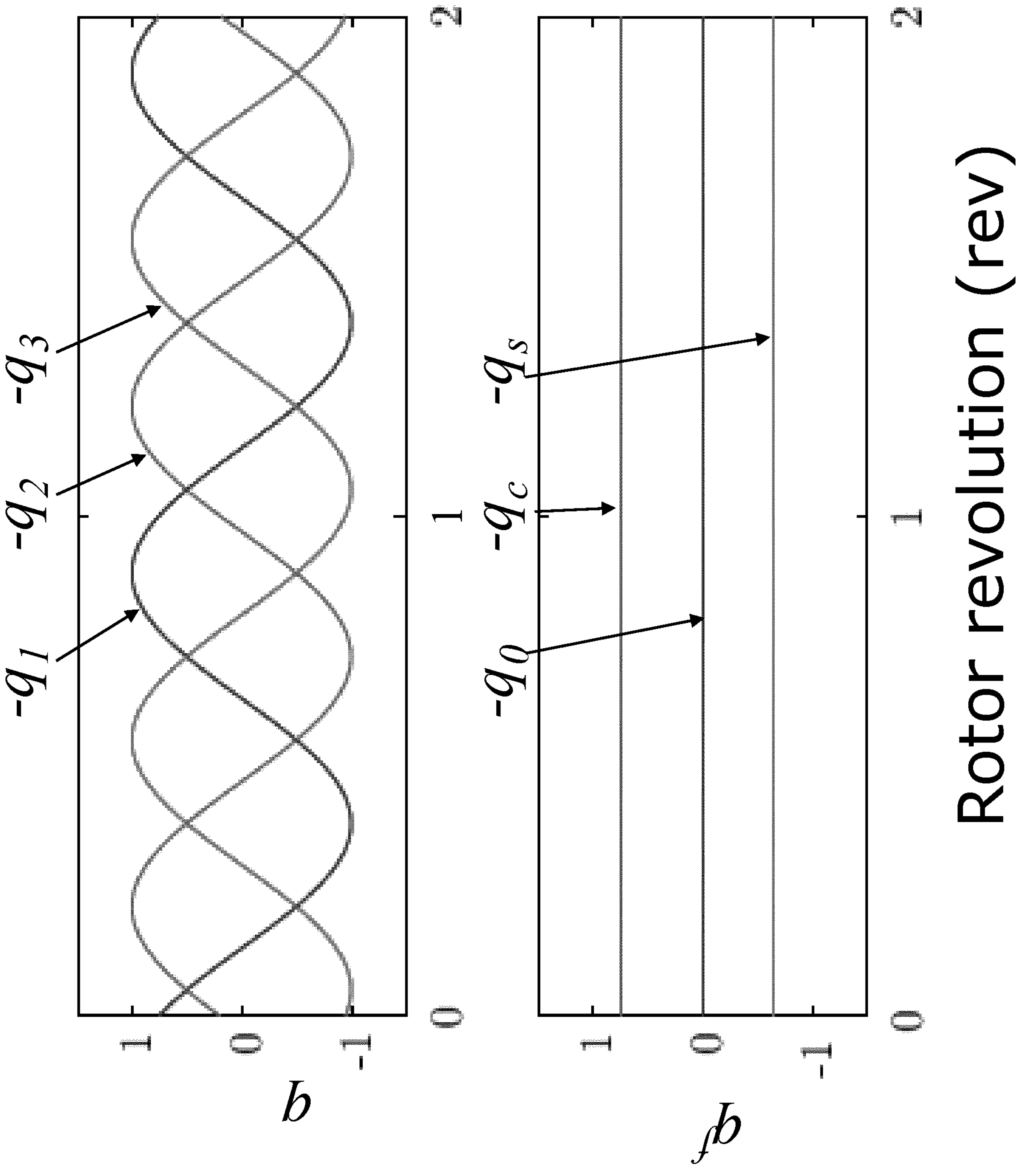


Fig. 3

Additive
pertubation

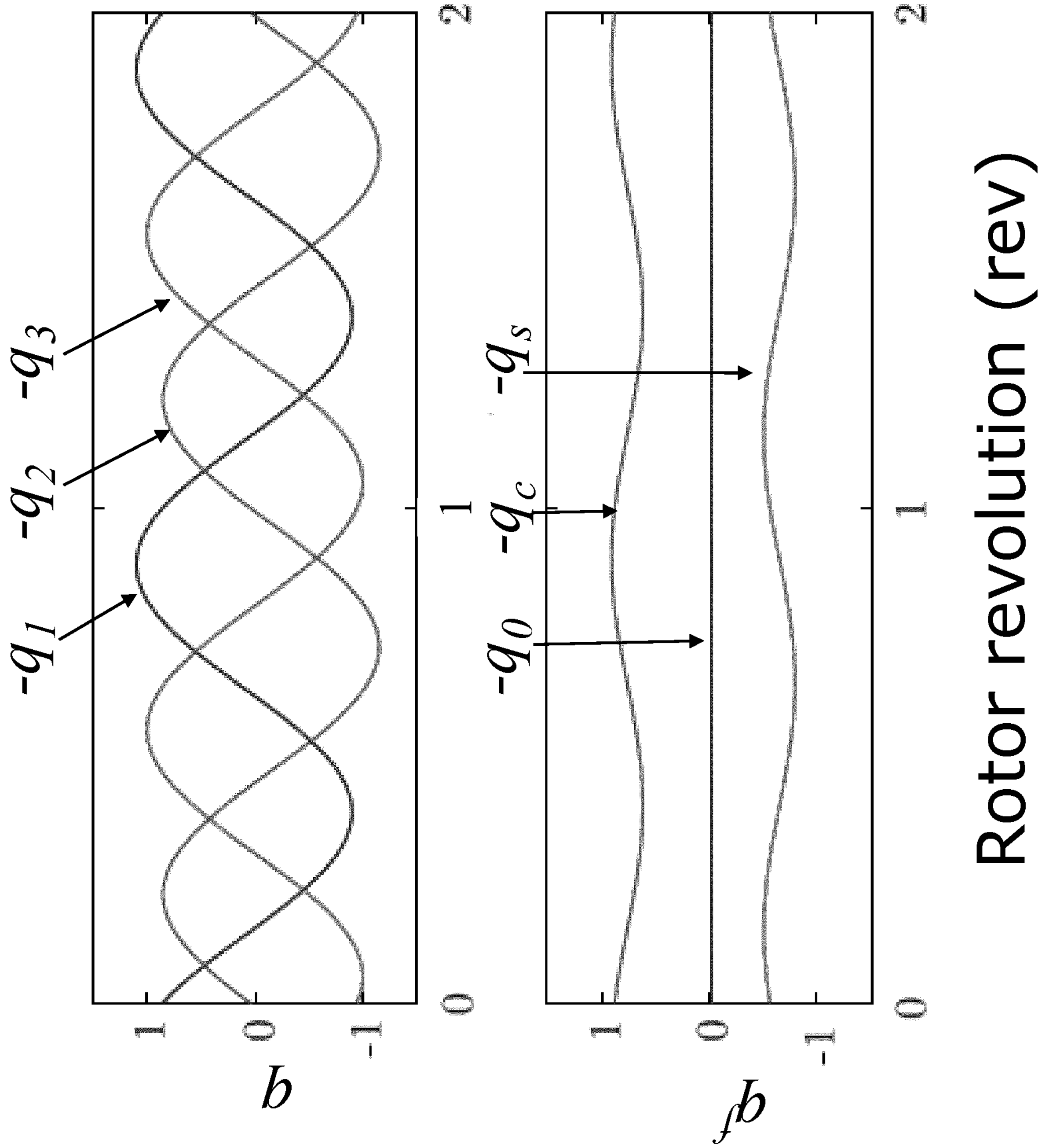


Fig. 4

Multiplative
pertubation

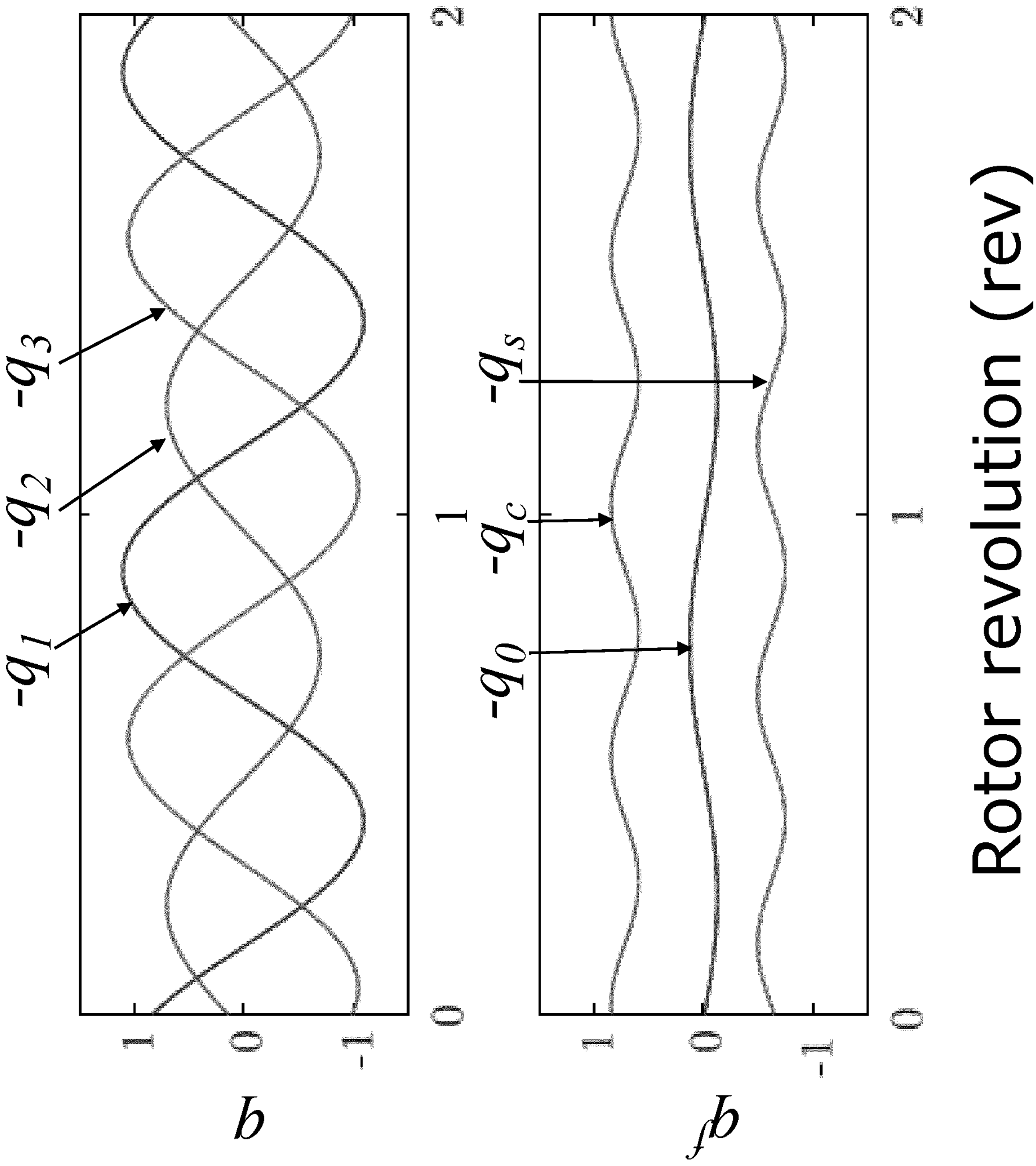


Fig. 4 (cont)

Multiplative and additive pertubation

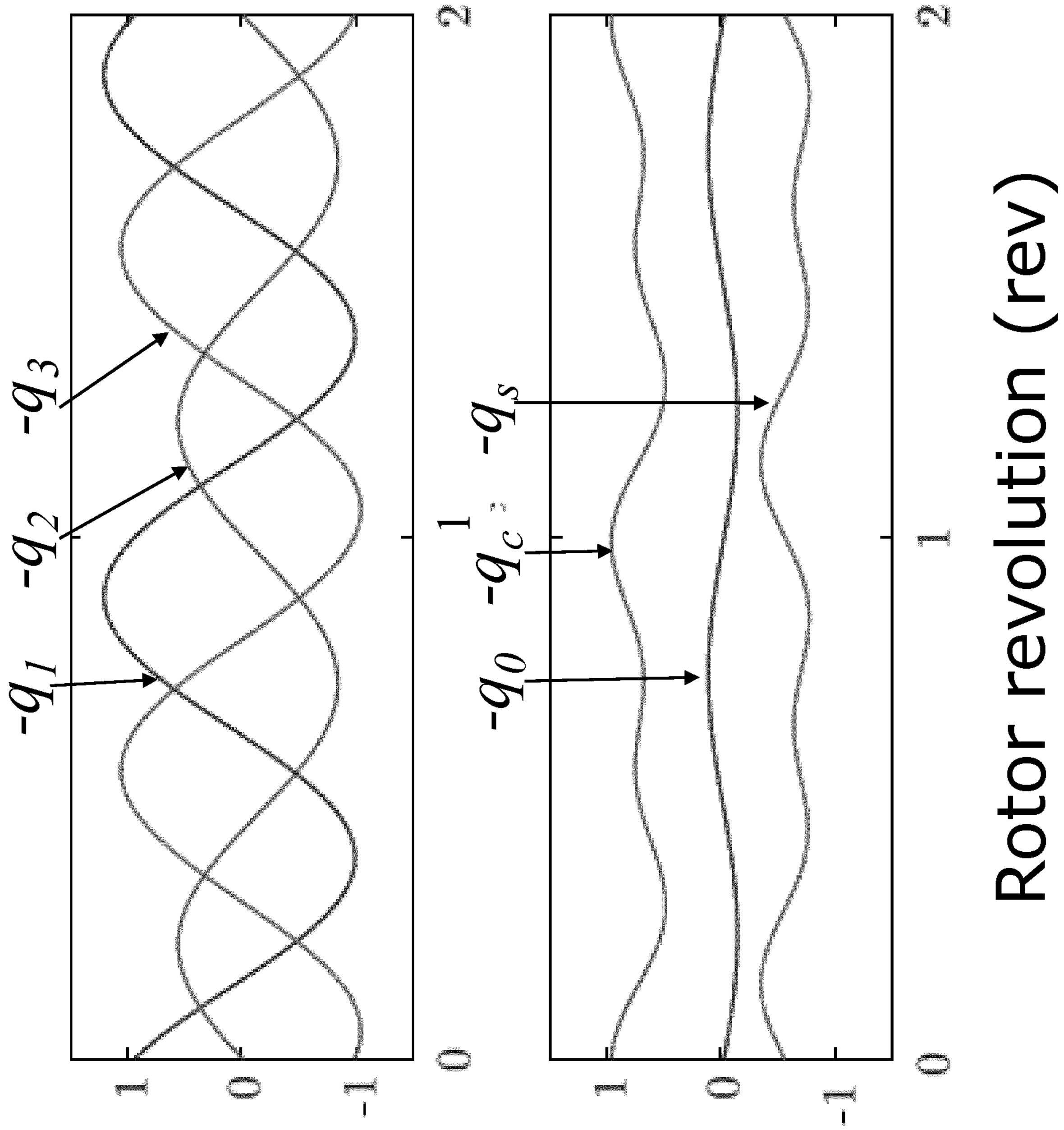


Fig. 5

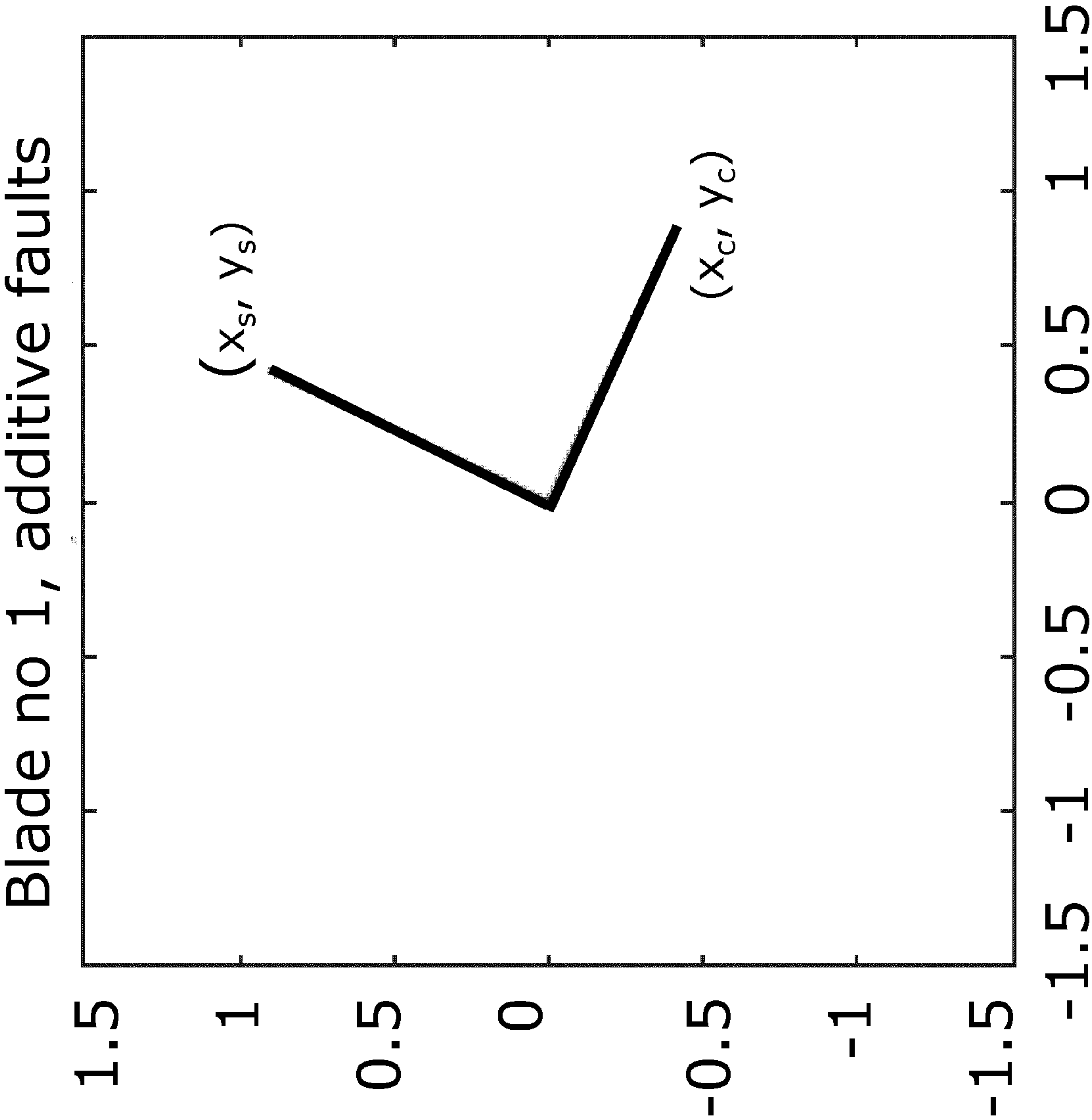
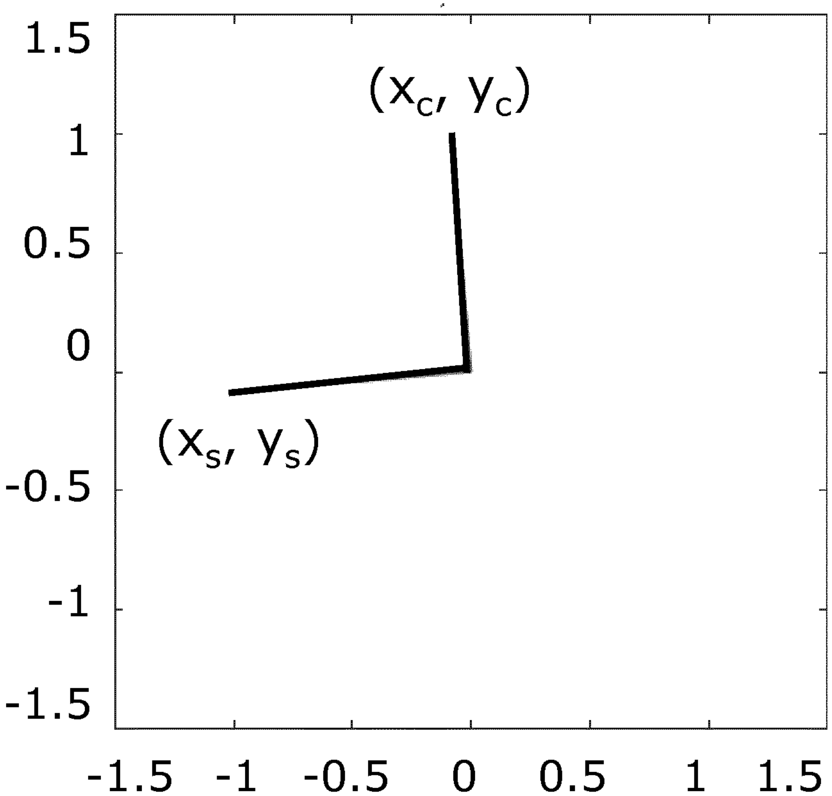

Blade no 1, additive faults
(xs, ys)
(xc, yc)
1.5
1
0.5
0
-0.5
-1
-1.5
-1.5
-1
-0.5
0
0.5
1
1.5

Fig. 6

Blade no 2, additive faults



Blade no 3, additive faults

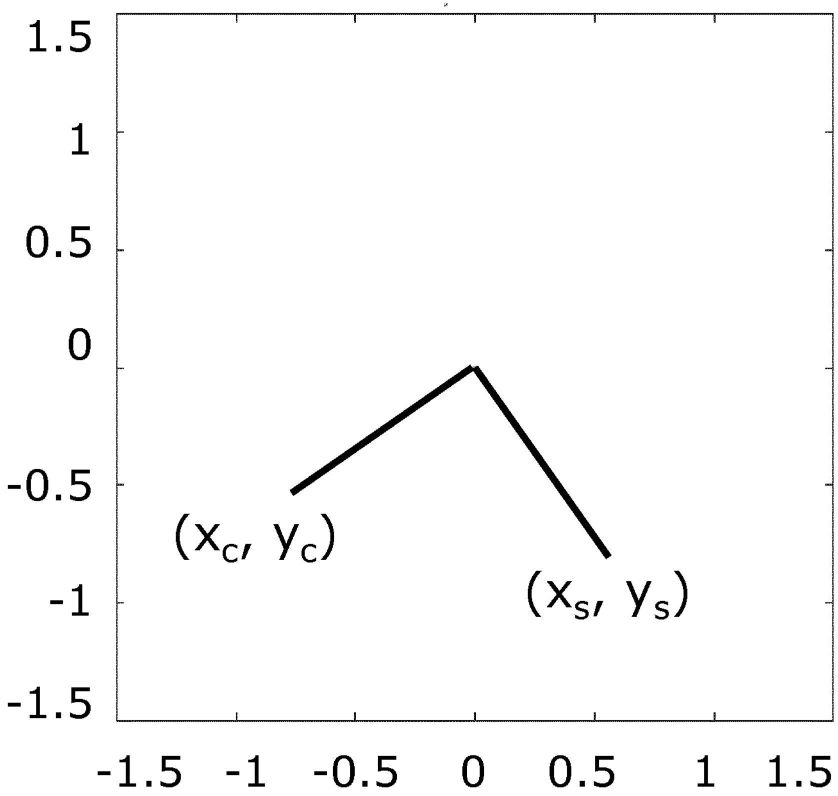


Fig. 6 (cont)

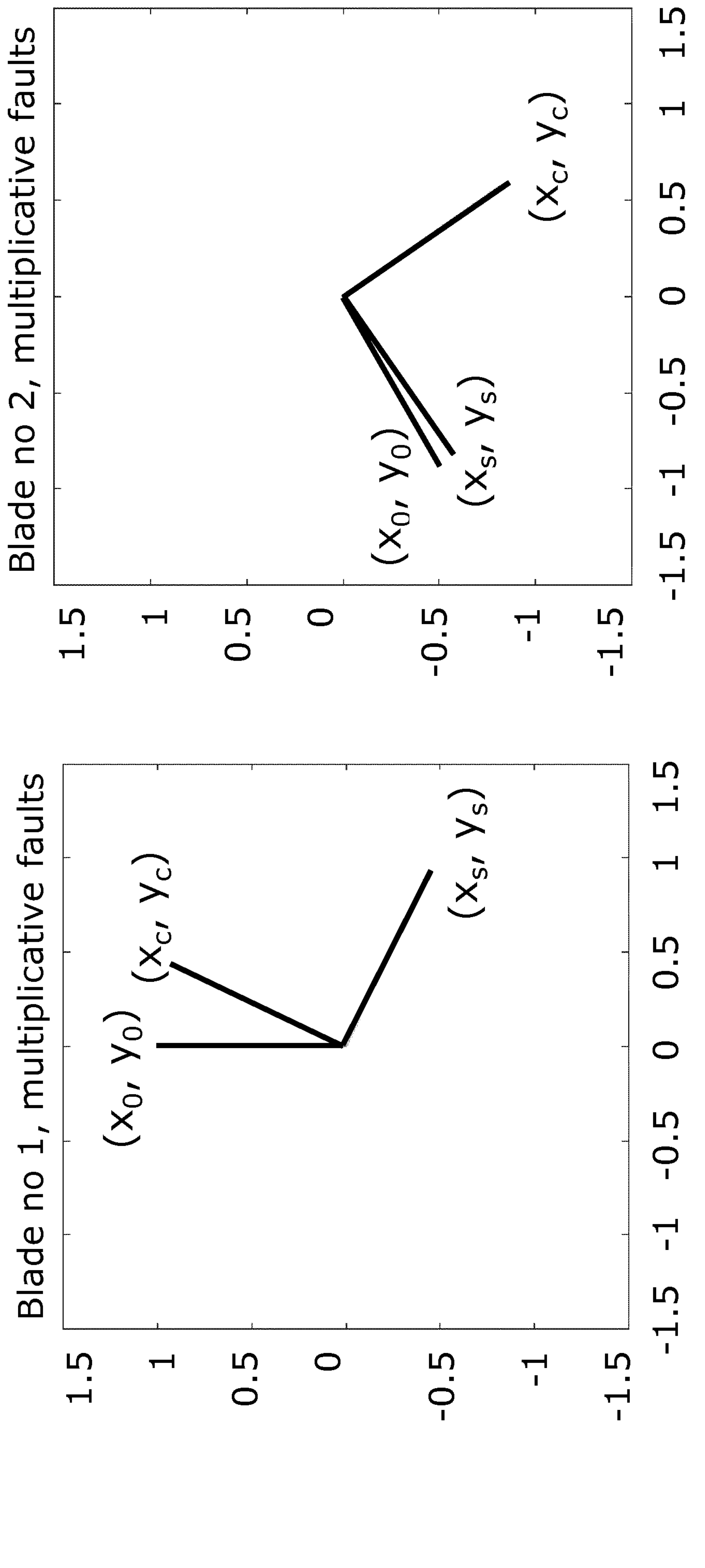

Blade no 1, multiplicative faults
(x_0, y_0)
(x_c, y_c)
(x_s, y_s)
Blade no 2, multiplicative faults
(x_0, y_0)
(x_s, y_s)
(x_c, y_c)
1.5
1
0.5
0
-0.5
-1
-1.5

Fig. 7

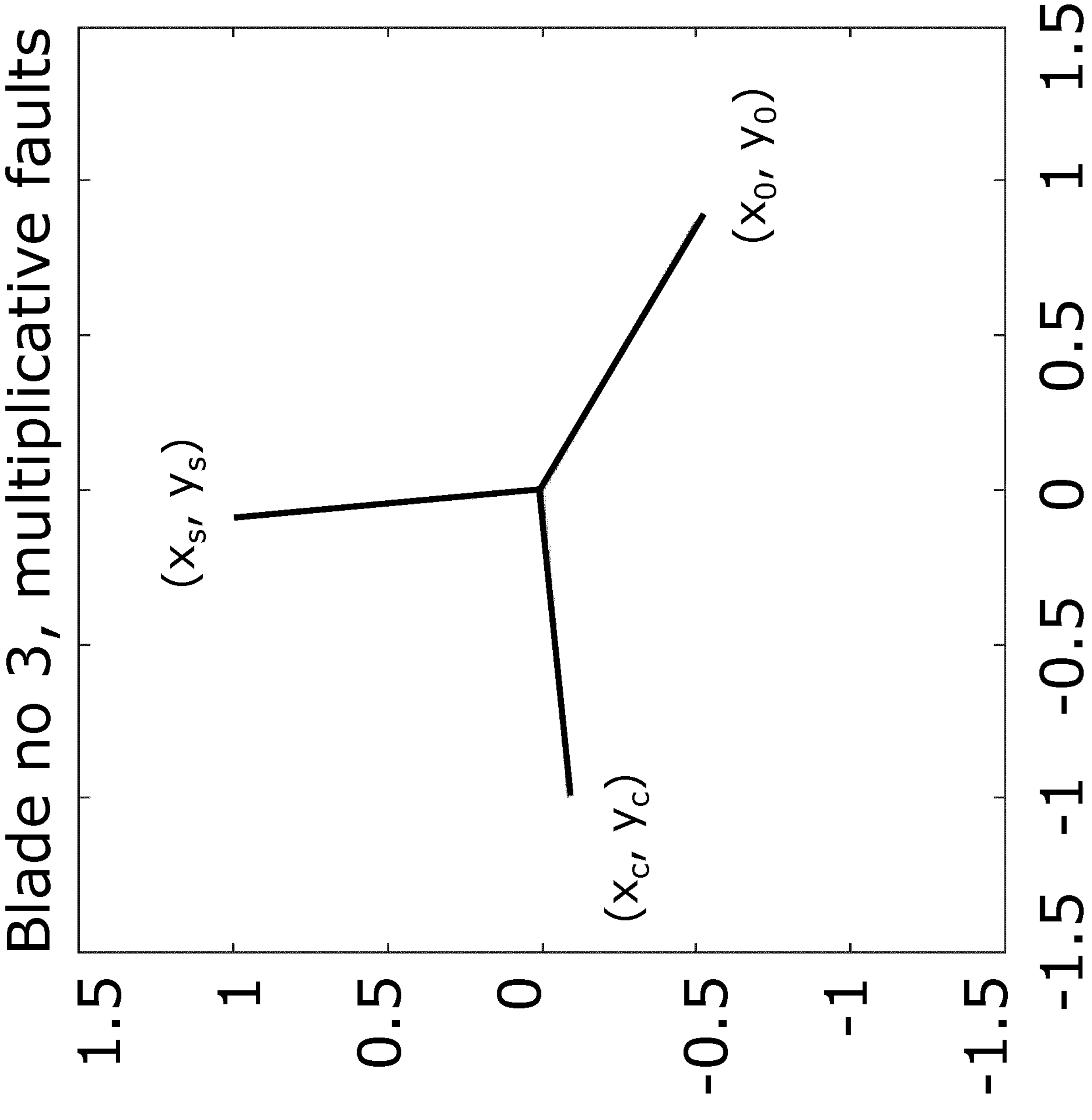

Blade no 3, multiplicative faults
(x_0, y_0)
(x_s, y_s)
(x_c, y_c)
1.5
1
0.5
0
-0.5
-1
-1.5

Fig. 7 (cont)

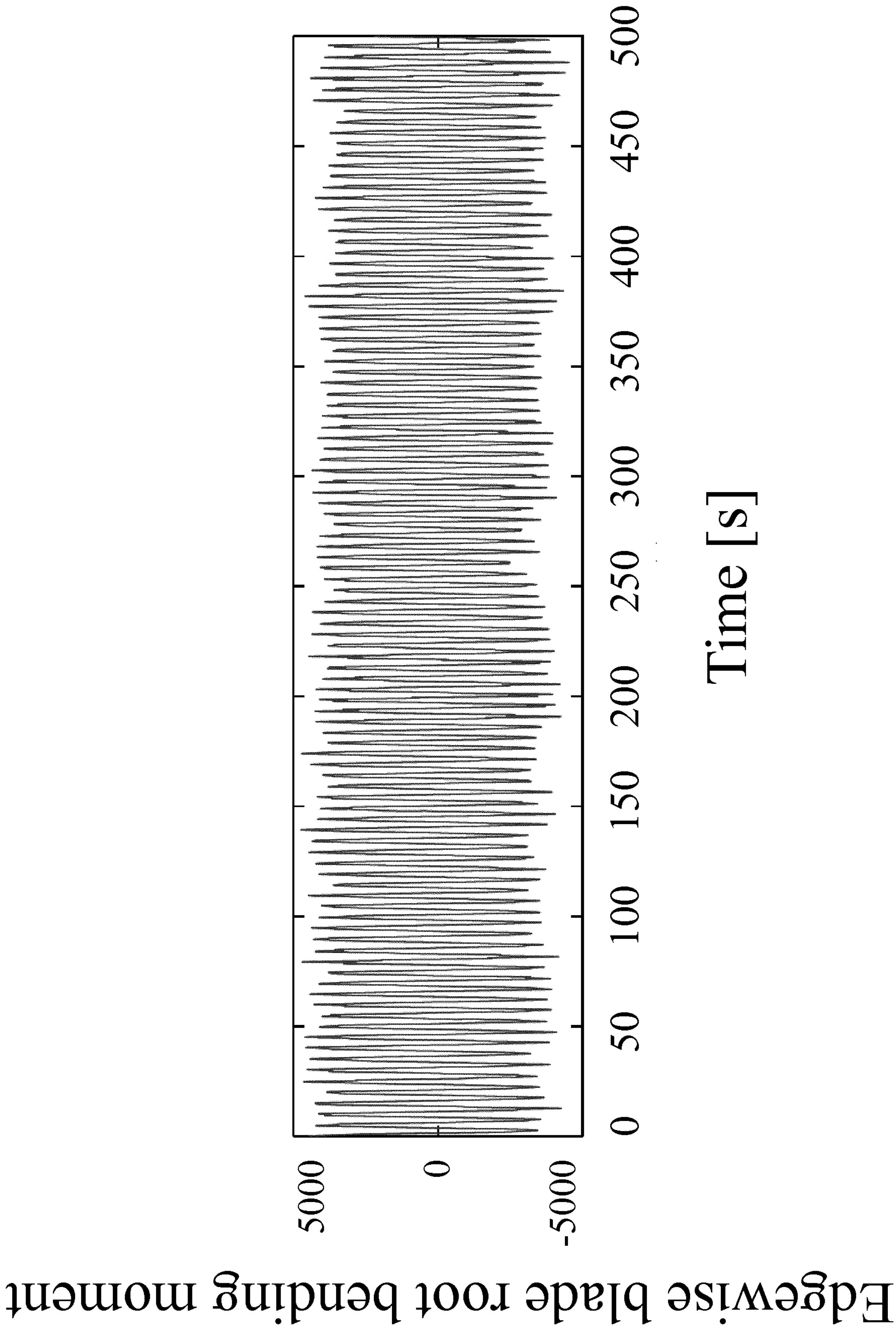

Edgewise blade root bending moment
5000
0
-5000
0
50
100
150
200
250
300
350
400
450
500
Time [s]

Fig. 8

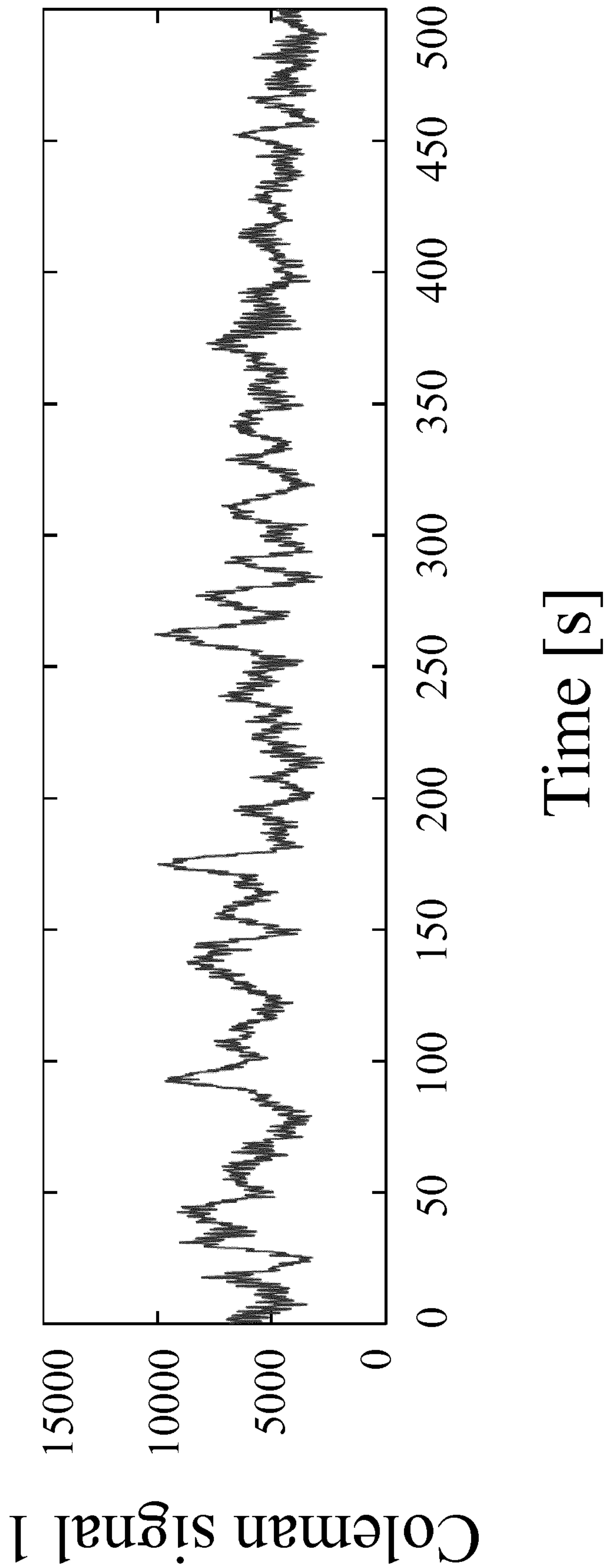

Coleman signal 1
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
500
Time [s]

Fig. 9

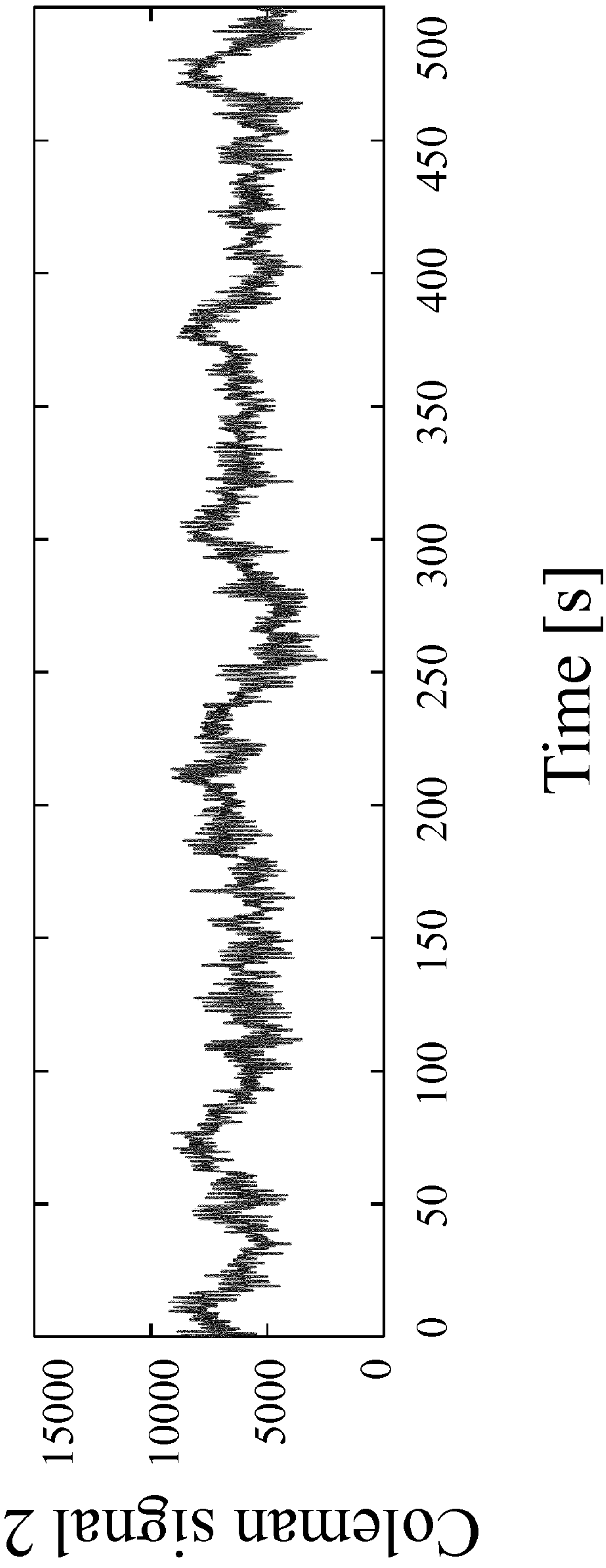

Coleman signal 2
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
500
Time [s]

Fig. 9 (cont)

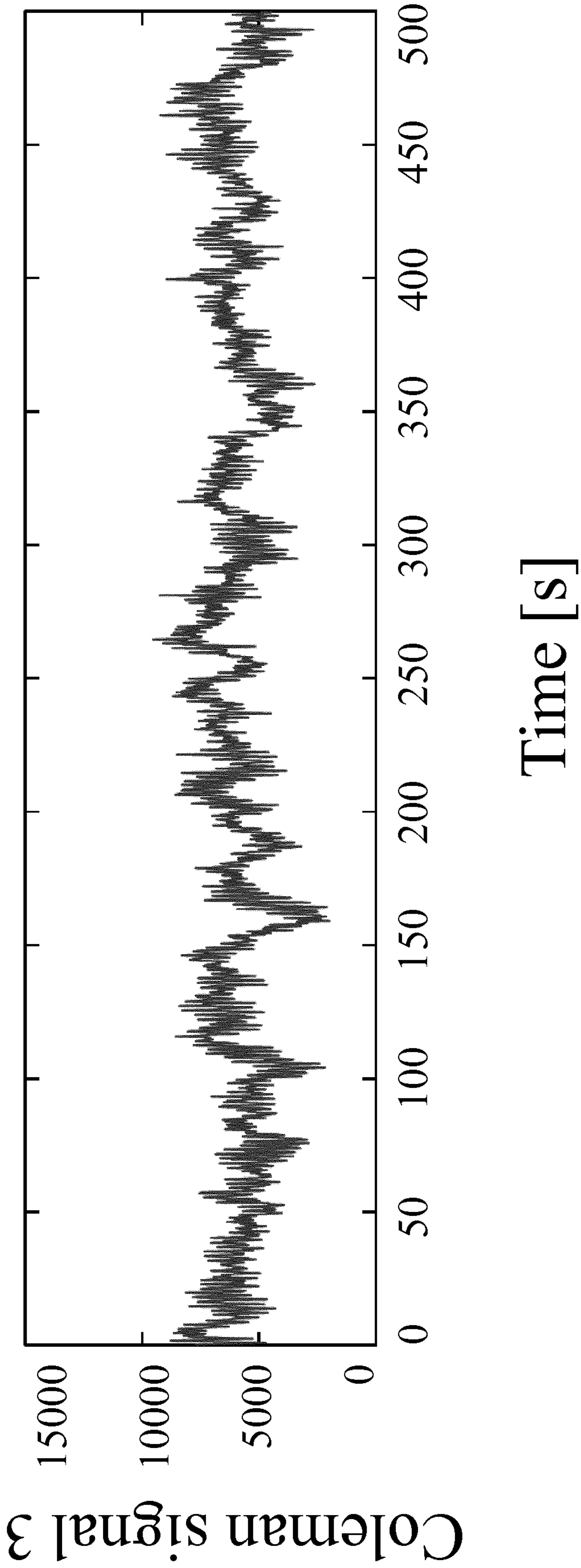

Coleman signal 3
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
500
Time [s]

Fig. 9 (cont)

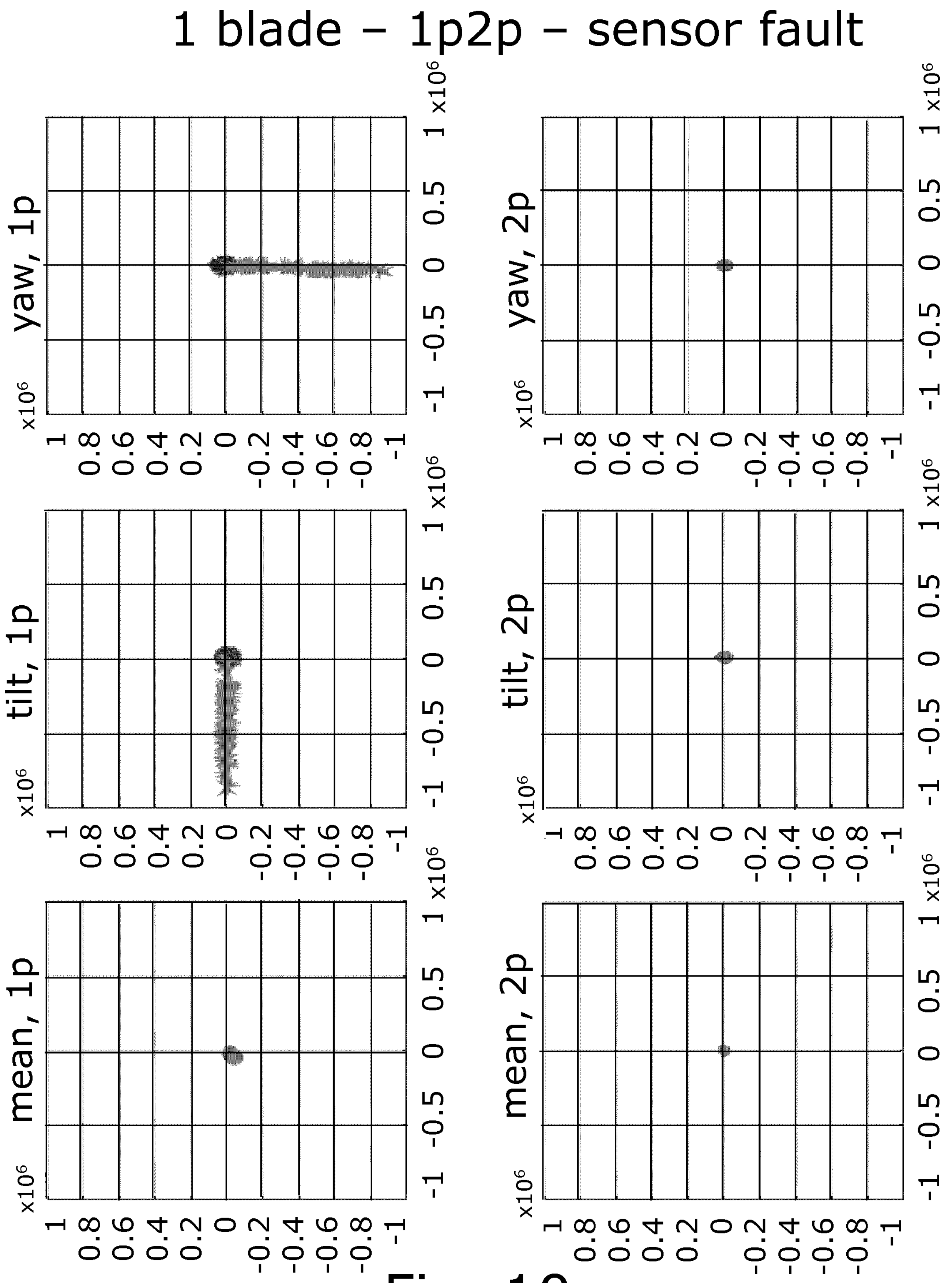

1 blade – 1p2p – sensor fault
yaw, 1p
tilt, 1p
mean, 1p
yaw, 2p
tilt, 2p
mean, 2p
x10⁶
1 0.5 0 -0.5 -1
1 0.8 0.6 0.4 0.2 0 -0.2 -0.4 -0.6 -0.8 -1

Fig. 10

3 blade – 1p2p – sensor fault

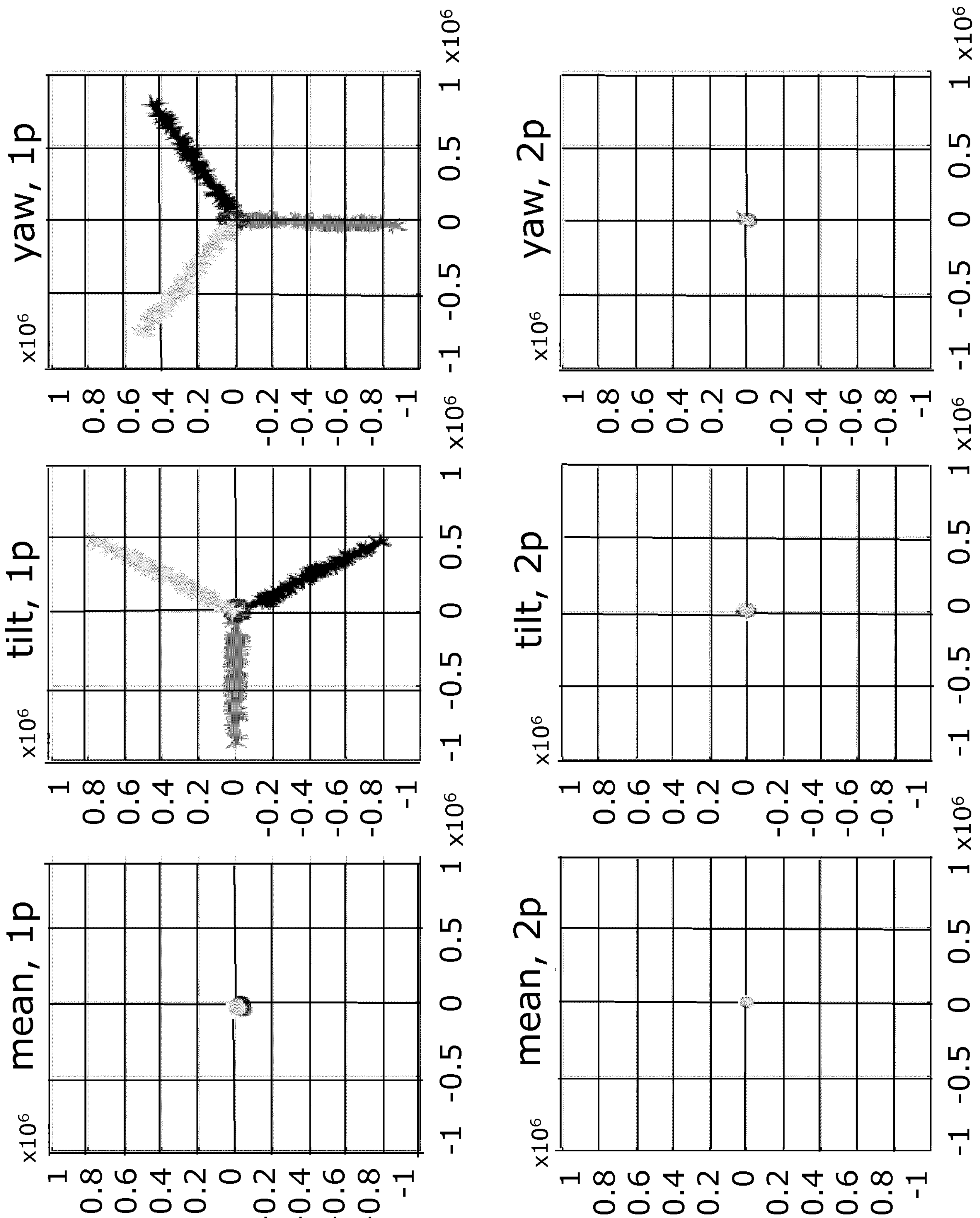


Fig. 11

1 blade – 1p - mass imbalance

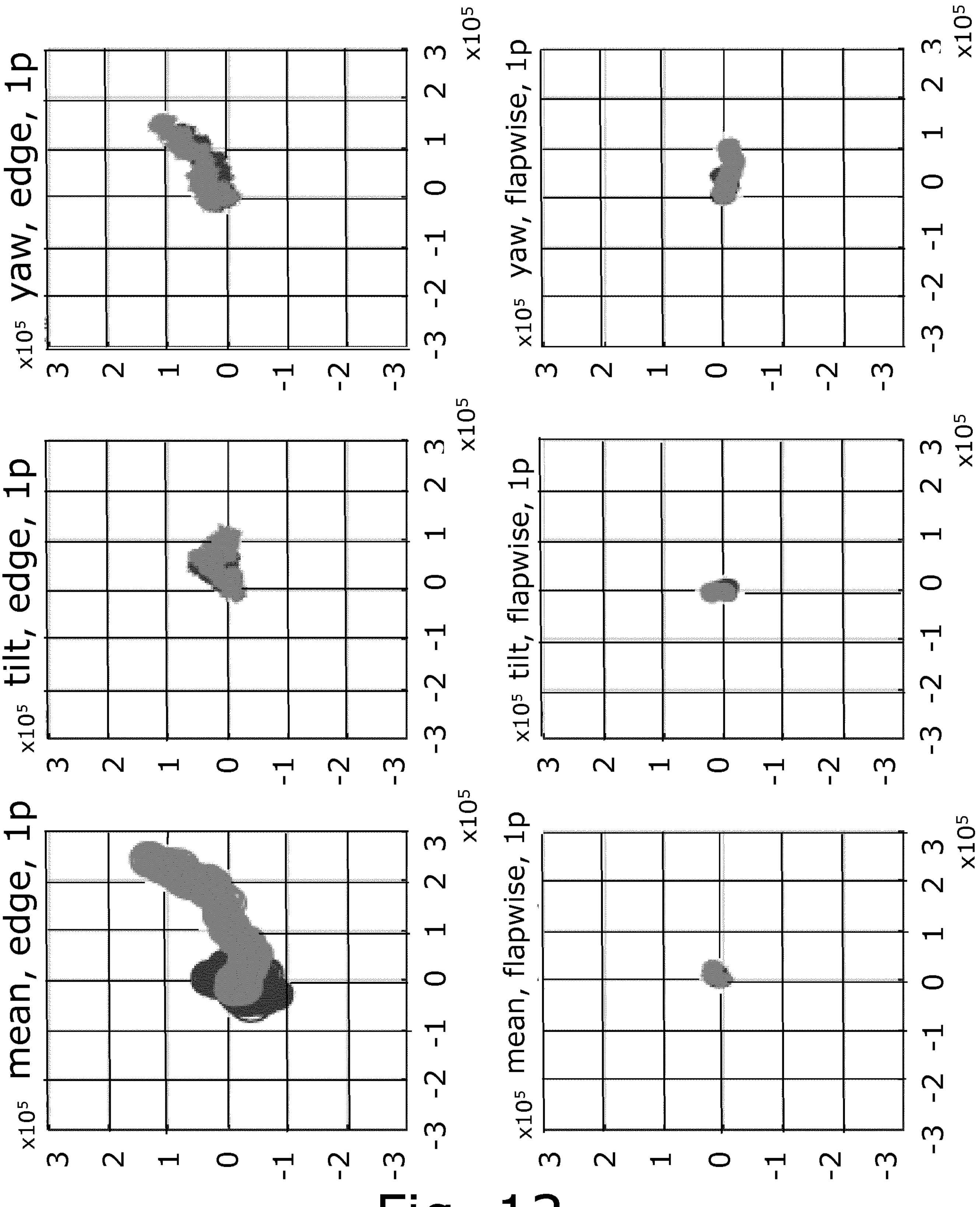


Fig. 12

1 blade – 2p - mass imbalance

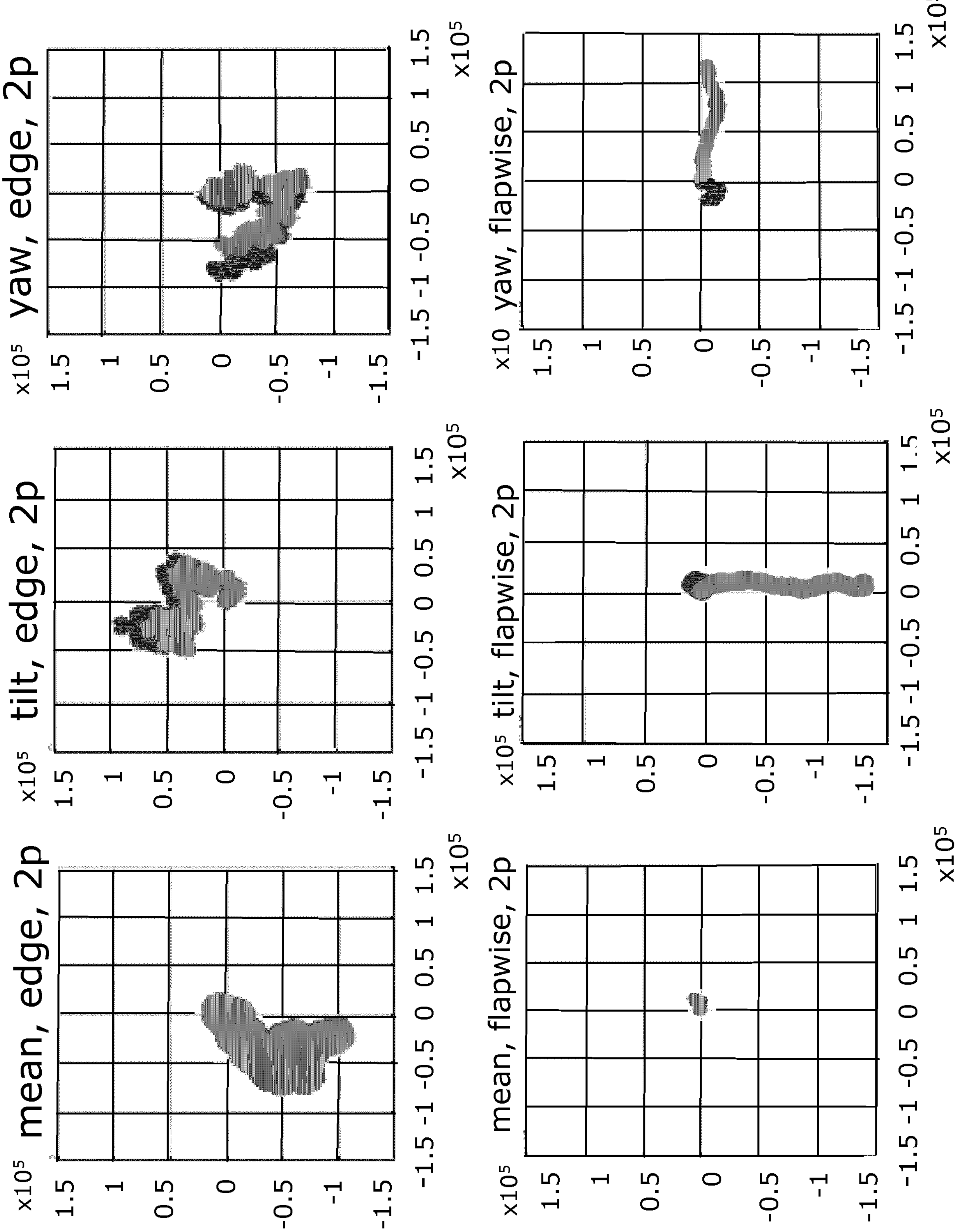


Fig. 13

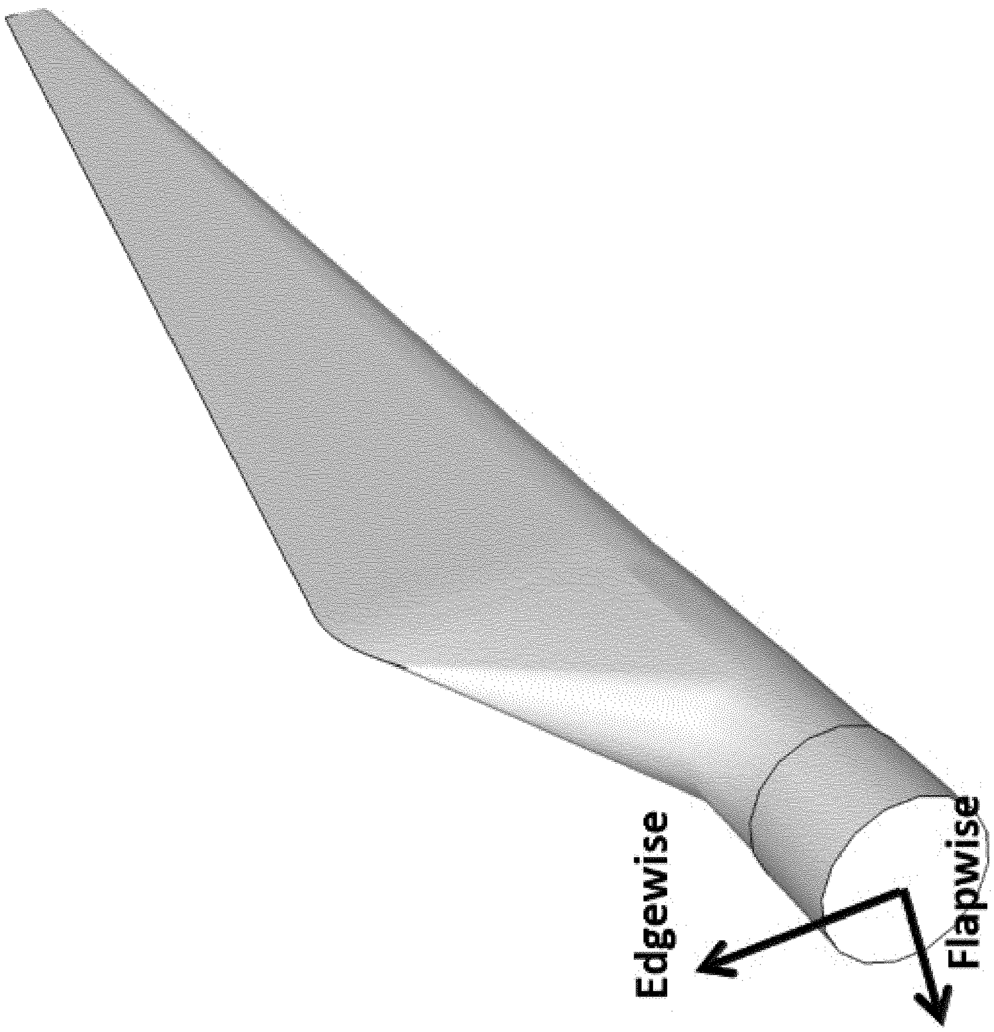


Fig. 14

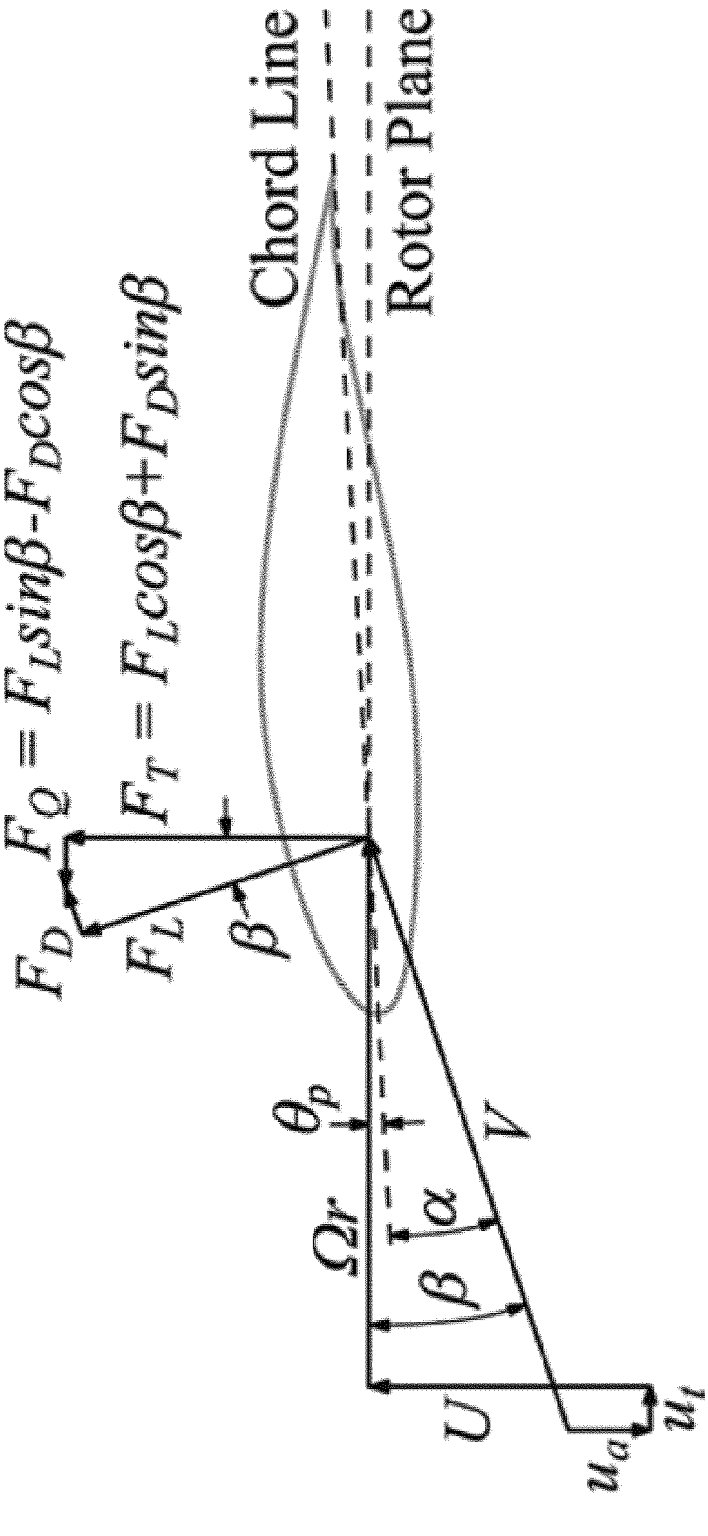

Chord Line
Rotor Plane
$F_Q = F_L sin\beta - F_D cos\beta$
$F_T = F_L cos\beta + F_D sin\beta$
F_Q
F_T
F_D
F_L
β
θ_p
Ωr
α
β
V
U
u_a
u_t

Fig. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/079637

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03D17/00 G01M1/14
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03D G01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	XIUKUN WEI ET AL: "Fault detection of large scale wind turbine systems", COMPUTER SCIENCE AND EDUCATION (ICCSE), 2010 5TH INTERNATIONAL CONFERENCE ON, IEEE, PISCATAWAY, NJ, USA, 24 August 2010 (2010-08-24), pages 1299-1304, XP031769909, ISBN: 978-1-4244-6002-1 the whole document ----- -/--	1-14

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 February 2017	20/02/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Libeaut, Laurent

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/079637

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	XIUKUN WEI ET AL: "Fault detection of large scale wind turbine systems: A mixed H[infinity]/H- index observer approach", CONTROL AND AUTOMATION, 2008 16TH MEDITERRANEAN CONFERENCE ON, IEEE, PISCATAWAY, NJ, USA, 25 June 2008 (2008-06-25), pages 1675-1680, XP031308446, ISBN: 978-1-4244-2504-4 the whole document -----	1-14
X	US 2005/276696 A1 (LEMIEUX DAVID L [US]) 15 December 2005 (2005-12-15) paragraph [0040] -----	1,2,6-14
X	G. Bir: "Multiblade Coordinate Transformation and Its Application to Wind Turbine Analysis", Conference Paper, NREL/CP-500-42553, 1 January 2008 (2008-01-01), pages 1-14, XP055277059, Retrieved from the Internet: URL:http://www.nrel.gov/wind/pdfs/42553.pdf [retrieved on 2016-06-01] the whole document -----	1,5, 10-14
X	JASON LAKS ET AL: "Multi-Blade Coordinate and direct techniques for asymptotic disturbance rejection in wind turbines", DECISION AND CONTROL (CDC), 2012 IEEE 51ST ANNUAL CONFERENCE ON, IEEE, 10 December 2012 (2012-12-10), pages 2557-2562, XP032323765, DOI: 10.1109/CDC.2012.6426004 ISBN: 978-1-4673-2065-8 Section II, page 2558 -----	1,2,5, 10-14

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2016/079637

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		DE 102005016524 A1	29-12-2005
		DK 177717 B1	07-04-2014
		DK 177769 B1	23-06-2014
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