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(54) Benævnelse: **FREMGANGSMÅDE TIL REGISTRERING OG MODELLERING AF ET OMGIVENDE VINDFELT VED HJÆLP AF EN LIDAR-SENSOR**

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Fortsættes ...

Description

The present invention relates to the field of LiDAR (Light Detection And Ranging) sensors used as a remote sensing means for measuring wind speed. It also relates to the field of wind turbines equipped with a LiDAR sensor, as well as to controlling these wind turbines.

The performance of LIDAR sensors in terms of precision, reliability and availability of measurements makes it possible to generate estimations and predictions of a wind state for a volume of aerosol targeted. However, LiDAR sensors have certain limitations in terms of precision and availability of the data. On the one hand, they supply only a raw measurement of the wind, that is to say a projection of the wind on a measurement axis (also called a LASER (Light Amplification by Stimulated Emission of Radiation) beam) and, on the other hand, they make it possible to access only a limited and noisy passband of the spectral content of the wind. As the raw measurement is an indirect measurement of the wind which corresponds to the projection of the wind on the axis of a LASER beam, it is then necessary to combine a plurality of raw measurements of a plurality of beams (or measurement axes) of distinct directions in order to obtain a precise estimation of the wind vector.

Such estimations are, however, not trivially or directly accessible, and require precise and robust reconstruction algorithms linked to the variable quality of the signal, to the geometry of the sensor and to the wind conditions to be designed and perfected.

The majority of reconstruction methods generated hitherto rest on the hypothesis of a wind field which is homogenous and stable over the whole surface area swept by the rotor, as is described in the publication *'A tutorial on the dynamics and control of wind turbines and wind farms', In 2009 American Control Conference. IEEE. 2009, pp. 2076-2089*.

However, this hypothesis is neither representative nor realistic, given that wind speed varies considerably as a function of altitude, within the atmospheric boundary layer, with very complex dynamics.

The publication by P Towers and B Ll Jones, *'Real-time wind field reconstruction from LiDAR measurements using a dynamic wind model and state estimation', In Wind Energy 19.1 (2016), pp. 133-150*, proposes an estimation algorithm for reconstructing a wind field. The approach consists in using an unscented Kalman filter incorporating a flow model based on the simplified Navier-Stokes equations. However, this technique supplies a reconstruction in two dimensions (2D) of the wind field, at a fixed altitude. In addition, the technique as described in this publication rests on an unrealistic hypothesis, which is that all the measurements of the LiDAR are available for all the beams, at the same instant.

Finally, a reconstruction algorithm proposed by certain LiDAR sensor manufacturers is also known. The principle is, in this case, to obtain an instantaneous estimation of the wind speed at unmeasured points in space, from interpolations on the measurements. However, in such cases it is possible to obtain, in real time and online, only an estimation of the component of the wind in the axis of the LiDAR. The longitudinal wind speed and direction are obtained only from a rolling average, and are not usable for applications in real time. The document by F. GUILLEMIN ET AL: "Nacelle LiDAR online wind field reconstruction applied to feedforward pitch control", JOURNAL OF PHYSICS: CONFERENCE SERIES, vol. 753, 1 September 2016, page 052019, XP055451670, describes an algorithm for reconstructing the wind field in front of a wind turbine in order to control the pitch of the blades of the wind turbine in a feedforward fashion.

In the field of wind turbines, the productivity of wind turbines and the maintenance costs are highly dependent on the monitoring capacity of the system, and in particular on the capacity to use relevant wind information. Indeed, the main sources of damage inflicted on the structure and on the members of the wind turbine are linked to wind conditions involving extreme loading (turbulent high wind, gusts) and to the wear of the materials subjected to vibratory and oscillatory phenomena. The latter are caused by interactions between the wind turbine and the wind field, notably with problems of vibrations exciting the fundamental modes of the wind turbine. There are certain control strategies which are currently implemented, but they do not have wind information which is reliable and may be incorporated into the control loop in order to ensure the anticipated usage period. In certain cases, the speed of the rotor is regulated by generator torque and aerodynamic torque (via the orientation of the blades). In other cases, there is no direct use of the wind measurement in the control loop, this meaning that the speed of the rotor is regulated retroactively. An alignment may also be obtained from an anemometric sensor situated in a turbulent region (nacelle) and subjected to drift, this leading to a wind turbine which is often misaligned.

In any case, this requires constraints to be incorporated into the design of the wind turbine, with reinforced structures and associated extra investment cost, and also with an associated loss in production and risk of loading the structure.

In order to remedy the aforementioned drawbacks, a first aspect of the invention therefore consists in developing an improved method for estimating the speed and the direction of a wind field in three dimensions (3D) online, in real time, in a volume situated upstream of a LiDAR sensor so as to have an estimation and a short-term prediction of the incident wind field on the LiDAR sensor. A second aspect of the invention aims to use this method and this LiDAR sensor in a strategy for controlling a wind turbine so as to obtain predictions of the loading of the rotor of the wind turbine, to detect gusts, turbulence, shear, etc.

To this end, the invention relates to a method for acquiring and modelling, by a LiDAR sensor, an incident wind field in a space situated upstream of said LiDAR sensor. For the method the following steps are performed:

a) a step of meshing of the space situated upstream of said LiDAR sensor in which the mesh of the space is produced by a set of discretized points positioned according to a predefined three-dimensional grid which comprises a set of meshes composed of estimation points and measurement points.

The meshing step makes it possible to discretize (or sample) the space upstream of the LiDAR sensor as a three-dimensional grid composed of discretized points and to be able to make these different discretized points coincide either at measurement points or at estimation points which are necessary to the modelling method. It furthermore makes it possible to position the measurement and estimation points in relation to each other and to know the distances separating all of these discretized points.

b) a step of measurement of the amplitude and of the direction of the wind at the different measurement points situated in the space upstream and positioned at at least two distinct distances from the LiDAR sensor, along at least three measurement axes.

The measurements made in this step make it possible to obtain sufficient and reliable initial data to be fed to an algorithm intended to estimate the amplitude and the direction of the wind on the estimation points.

c) a step of estimation of the amplitude and of the direction of the wind at any instant over all of the estimation points and the estimation is made by means of optimization by a recursive least squares method weighted by a cost function $J(t)$ which uses at least the data from the measurement points, spatial wind speed consistency data, temporal wind speed consistency data, and data qualifying the quality of the measurements performed on the measurement points and said cost function $J(t)$ at any instant (t) is expressed in the form defined in the paragraph linking pages 5 and 6 of the patent application.

Taking into account these different parameters in a cost function to be optimized is what will make it possible to access an estimation of the amplitude and of the direction of the wind on each estimation point of the mesh.

d) a step of reconstruction, in real time and within a defined reference frame, of the incident wind field in three dimensions (3D) from the amplitudes and the directions of wind estimated and measured for each point.
This step makes it possible to reconstruct, in 3D and in the volume sampled by the three-dimensional grid, the incident wave field. In this step a history of the LiDAR measurements is made, this making it possible to know the past states of the wind field, and this history is incorporated into the synthesis of the current and future estimations of the 3D wind field, this making possible a reconstruction in real time.
The advantage of using an approach by means of optimization, using a recursive form of weighted least squares, is to be able to determine a complete image in three dimensions (3D) of the incident wind propagating in the space situated upstream of the LiDAR sensor.

According to one aspect of the invention, the measurement *m* of the amplitude and of the direction of the wind at a measurement point is given by a relationship of the form:

$$m_{j,x}(k) = a_j v_{j,x}(k) + b_j v_{j,y}(k) + c_j v_{j,z}(k)$$

in which $v_{j,x}(k)$, $v_{j,y}(k)$, $v_{j,z}(k)$ are values of the wind speed projected on a reference frame x, y, z at an initial time (k), and a_j, b_j, c_j with j = 0, 1, 2, 3, 4 are measurement coefficients, which are given as,

$$\begin{cases} a_j = \cos(\theta_j), \\ b_j = \sin(\theta_j)\cos(\varphi_j), \\ c_j = \sin(\theta_j)\sin(\varphi_j) \end{cases}$$

in which θ_j, φ_j are, respectively, the zenith and the azimuth of the measurement axis in a spherical coordinate system.

In this manner the wind vector, at each instant sampled, for all of the points of the space is composed of the three components which will make it possible to determine the complete image in three dimensions. Furthermore, the choice of the measurement coefficients makes it possible to depend only on the angles of the beams and are not a function of the measurement distances, this facilitating the computer programming of the cost function *J*.

The core of the invention is defined by the cost function *J* at any instant (t) expressed in the following form:

$$J(t) = (\omega(0) - \hat{\omega}(0))^T P_0^{-1} (\omega(0) - \hat{\omega}(0)) + \sum_{j=1}^{t} (\omega(j) - \omega(j-1))^T Q^{-1} (\omega(j) - \omega(j-1)) + \\ + \sum_{j=1}^{t} \omega(j)^T C_s^T R_s^{-1} C_s \omega(j) + \sum_{j=1}^{t} (C_m \omega(j) - m_m)^T R_m^{-1} (C_m \omega(j) - m_m(j))$$

in which ω is an ordered vector composed of all the components of the speed of the points of the space where the wind is estimated, $\hat{\omega}(0)$ is the estimation of the wind speed at the time 0, P_0, Q, R_s and R_m are weighting matrices of appropriate dimension, and C_s, C_m are matrices which take into account the wind speed and the measurement noises.

Using such a cost function, it is possible to estimate the wind speed at an estimation point. Furthermore, such a function makes it possible to obtain a clear interpretation of the weighting matrices P_0, Q, R_s and R_m.

According to one aspect of the invention, the measurements of the amplitude and of the direction of the wind at the different measurement points are performed with a sampling rate of at least 0.25 Hz. The use of such a range of sampling frequencies has the effect of obtaining a plurality of measurements simultaneously on the same measurement axis while at the same time obtaining measurements which are reliable and precise.

According to one aspect of the invention, the measurements of the amplitude and of the direction of the wind at the different measurement points are taken at at least two different distances along the measurement axis. Measurements performed at at least two distances make it possible to define a three-dimensional volume which is sufficient to encompass the blades of a wind turbine, as will be described below.

According to one aspect of the invention, the measurements of the amplitude and of the direction of the wind are taken along at least three measurement axes. Having at least three measurement axes makes possible a fine meshing of the space upstream and also makes it possible to obtain a sufficient number of measurements for the step of estimation of the wind speed.

According to one aspect of the invention, the spatial consistency of the wind speed on the axes *x*, *y* and *z* of a Cartesian reference frame is estimated by a formula of the type:

$$C_x \omega \approx 0$$

with

$$C_x = \begin{bmatrix} C_l \\ C_t \\ C_v \end{bmatrix}$$

in which:

o C_l characterizes the variation of the wind speed for an estimation domain along the longitudinal axis *x* and

o C_t characterizes the variation of the wind speed for an estimation domain along the lateral axis *y* and

o C_v characterizes the variation of the wind speed for an estimation domain along the vertical axis *z* and

Such a characterization has the effect of making possible the computer coding of such a function.

According to one aspect of the invention, the spatial consistency of the wind speed on the axes *x*, *y* and *z* of the Cartesian reference frame is estimated with the following hypotheses:

o the variation of the wind speed along the longitudinal axis *x* is low and the partial derivative dv_x/dx is relatively small along the longitudinal axis,

o the wind changes smoothly along the lateral axis *y* and the partial derivative dv_x/dy is small along the lateral axis *y*,

o the wind changes with a power law on the vertical axis *z* which is given by:

$$v_l = v_r \left(\frac{z}{z_r}\right)^{\alpha}$$

in which α is an exponent of the power law, v_l is the longitudinal wind at an altitude z above the ground, and z_r a reference altitude.

Such hypotheses are realistic and make possible estimations of wind speeds which are reliable and precise.

According to one aspect of the invention, the quality of the measurements performed by the LiDAR is represented by a model of the form:

$$C_m w = m_m + \epsilon_m$$

in which ϵ_m describes the measurement noises.

The formulation of this type makes it possible to take into account the inaccuracies of the measurements of the LiDAR.

According to one aspect of the invention, the estimation of the amplitudes and of the directions of the wind field at an instant (t) over all of the estimation points is given by the following formula:

$$w(t) = w(t-1) + K(y(t) - Cw(t-1))$$

The preceding formula has the advantage of linking the estimations of the wind speed over time for the estimation points.

The invention also relates to a computer program product which comprises code instructions organized to implement the steps of the acquisition and modelling method described above. The program is run on a processing unit of the LiDAR.

The invention also relates to a LiDAR sensor which comprises, in memory, the code instructions of a computer program product as described above and which is organized to run such a computer program product.

In this manner, a LiDAR sensor which runs such a computer program product will send reliable information on an incident wind field in three dimensions and in real time.

One subject of the invention also relates to a wind turbine which comprises a LiDAR sensor as described above.

According to one aspect of the invention, the LiDAR sensor is disposed on the nacelle of said wind turbine.

Finally the invention also relates to a method for controlling and/or monitoring a wind turbine equipped with a LiDAR sensor and a driving logic controller, and the method comprises the following steps:

a) a step of generation of strategy of feedforward control of said wind turbine by using the reconstruction of the incident wind field in three dimensions and in real time,

b) a driving step incorporating the control strategy generated which consists in driving the pitch of the blades or the orientation of the nacelle.

In this manner making available sufficiently robust and precise information on the incident wind state on the approach to the rotor makes possible a new control approach, with the incorporation of a dynamic and preventative pre-positioning term. Furthermore, the capacity to reconstruct, online and in real time, an incident wind field on the approach to the rotor plane opens up numerous usage possibilities: quantification of the misalignment of the wind turbine, power curve, transfer function of the nacelle, detection of gusts, monitoring and diagnosis of the loading and of the risks of wear, optimization of preventative maintenance, analysis of the resource, optimization of production. This then makes it possible to increase the yield of wind turbines, to reduce maintenance costs, to increase the lifetime of components and to reduce investment costs by optimizing the design.

Brief presentation of the figures

Other features and advantages of the method according to the invention will become apparent on reading the below description of a non-limiting exemplary embodiment, referring to the appended figures described below.

Figure 1 illustrates a wind turbine equipped with a LiDAR sensor according to the invention.

Figure 2 illustrates the steps of the method for acquiring and modelling by the LiDAR sensor according to the invention.

Figure 3 is a front view of the mesh of the space according to the invention.

Figure 4 is a perspective view of the mesh of the space according to the invention.

Figure 5 illustrates a wind field in 3D reconstructed from the measurements of the LiDAR in a particular case.

Figure 6 illustrates the steps of the method for driving the wind turbine according to the invention.

Detailed description of the invention

Notation

Over the course of the description, the following notation is used:

- x, y, z: directions of the three-dimensional reference frame, with z the vertical axis and x the main direction of the wind.
- θ and φ: orientation angles of said LiDAR sensor. These angles are explained in Figure 1: the angle θ is the angle made by the projection of the measurement axis of the LiDAR in the plane (y, z), and φ is the angle made by the projection of the measurement axis of the LiDAR in a plane composed of the axis x and of the projection of the measurement axis of the LiDAR in the plane (y, z).
- $m(t)$: measurement of the LiDAR sensor at a measurement point.
- $v_{j,x}(k)$, $v_{j,y}(k)$, $v_{j,z}(k)$: projections of the wind speed on x, y, z.

- ω: ordered vector composed of all the components of the wind speed at the points of the space where the wind is estimated on the axes x, y and z of the three-dimensional reference frame.
- $\hat{\omega}(t)$: estimation of $\omega(t)$ at the instant t.
- P(t): time-variant auxiliary matrix, which may be obtained at the instant t.
- P_0, Q, R_s and R_m are weighting matrices of appropriate dimension.

In the rest of the description, the term "LiDAR" is used to denote a LiDAR sensor.

The invention relates firstly to a method for acquiring and modelling, by a LiDAR sensor, an incident wind field with the aim of estimating the speed and the direction of the wind for a wind field on the approach to and upstream of the LiDAR, and to do so as reliably as possible. This estimation must be made online, in real time, for a 3D wind field sampled.

Figure 2 shows the different steps of the acquisition and modelling method according to the invention:

1. Meshing (MA) of the space situated upstream of said LiDAR sensor, the mesh comprising estimation points (PE) and measurement points (PM).
2. Measurement (MES) of the amplitude and of the direction of the wind at the different measurement points (PM).
3. Estimation (EST) of the amplitude and of the direction of the wind at any instant (t) for all of the estimation points (PE).
4. Reconstruction (MOD 3D) of the incident wind field in three dimensions (3D) and in real time over all of the discretized points.

Figure 1 shows a wind turbine 1 equipped with a LiDAR sensor 2. The LiDAR sensor 2 is used to measure the wind speed at a given distance at a measurement point PM. Advance knowledge of the wind measurement makes it possible *a priori* to give a lot of information.

There is a plurality of types of LiDAR sensor, for example scanned LiDAR, continuous LiDAR or pulsed LiDAR sensors. In the context of the invention, use is preferably made of a pulsed LiDAR. However, the other LiDAR technologies may be used while remaining in the scope of the invention. As may be seen in Figure 1, which is an exemplary embodiment, the LiDAR used comprises 5 beams or measurement axes (b0, b1, b2, b3, b4). Non-limitingly, the acquisition and modelling method also operates with a LiDAR comprising three beams or more. The 5-beam pulsed LiDAR sensor is mounted on a nacelle 3 of a wind turbine 1.

Conventionally a wind turbine 1 makes it possible to transform the kinetic energy of the wind into electrical or mechanical energy. For converting the wind into electrical energy, it is composed of the following elements:

- a tower 4 which makes it possible to place a rotor (which is not shown) at a sufficient height to make it possible for it to move (which is necessary for horizontal-axis wind turbines), or to place this rotor at a height which makes it possible for it to be propelled by a stronger and more regular wind than on the ground 6. The tower 4 generally houses some of the electrical and electronic components (modulator, control, multiplier, generator, etc.);
- a nacelle 3 mounted at the top of the tower 4, housing mechanical and pneumatic components and certain electrical and electronic components (which are not shown), which are necessary to the operation of the machine. The nacelle 3 may rotate in order to orientate the machine in the right direction;
- the rotor, fixed to the nacelle, which comprises a plurality of blades 7 (in general three) and the hub of the wind turbine. The rotor is propelled by the energy of the wind, it is connected by a mechanical shaft directly or indirectly (via a gearbox-mechanical shaft system) to an electric machine (electric generator, etc.) (which are not shown) which converts the energy received into electrical energy. The rotor is potentially provided with control systems such as variable-pitch blades or aerodynamic brakes;

- a transmission, composed of two shafts (mechanical shaft of the rotor and mechanical shaft of the electric machine) linked by a transmission (gearbox) (which are not shown).

In the description given below, the acquisition and modelling method described is theoretical and operates independently of the wind turbine 1. However, the different examples and developments are given for the case of a LiDAR mounted on the nacelle 3 of the wind turbine 1 so as to carry out the different steps of the acquisition and modelling method which are shown in Figure 2 at a certain altitude with respect to the ground 6.

In this part, the different steps of the acquisition and modelling method according to the invention are described:

1. Meshing (MA) of the space situated upstream of said LiDAR sensor

In this first step, the space upstream of the LiDAR sensor is defined according to a mesh, as may be seen in Figures 1, 3 and 4. In this step a coordinate system in which the Lidar performs measurements is defined. The coordinate system defined is the direct trihedron illustrated in Figures 1 and 3. The origins x-y of this system are at the position of the LiDAR on the nacelle 3, and the origin z is on the ground 6.

The axis x points horizontally in the direction of the wind, the axis z points vertically upwards and the axis y is perpendicular in order to form a direct three-dimensional reference frame (in accordance with the right-hand rule).

In this step, the mesh of the space comprises a set of discretized points which are placed upstream and which define a three-dimensional grid. For each fixed distance x, the plane y-z is divided into non-overlapping cells, as may be seen in Figure 3. The mesh comprises measurement points (PM) for measuring and estimation points (PE) for estimating the wind speed.

In connection with this mesh of the space, underlying variables, referred to as optimization variables, are also defined, which are necessary to the estimation step described below. In order to make possible an astute and effective implementation of the optimization algorithm described below, all the optimization variables are grouped into an ordered vector, denoted ω. The order determined for these optimization variables is an engineering element which is crucial to the feasibility and the performance of a coding algorithm for this method.

A vector ω is defined for each point of the space discretized and it is composed of all the components v_x of the points (PE) of the space where the wind is estimated, followed, respectively, by the components v_x and v_z. The estimation of the wind speed at n points involves the construction of a vector ω of size 3n, with w_1 to w_n containing all the v_x, w_{n+1} to w_{2n} containing all the v_y and w_{2n+1} to w_{3n} containing all the v_z.

The following example is given for the components v_x of the wind speed, it being understood that the method is identical for v_y and v_z. As was done in the initial step, and as may be seen in Figure 3, the space is discretized on x, y and z with n_x points on x, n_y points on y and n_z points on z.

In this configuration the following is obtained:

$$n = n_x n_y n_z$$

The component v_x of the wind speed, the coordinate of which is $(x_i,\ y_j,\ z_k)$, is defined by $v_{i,j,k}$. The index l of w_l, where the corresponding estimation is situated, is obtained thus:

$$l = (n_x - i)n_y n_z + (k - 1)n_y + j$$

For example, if i = n_x, k = 1 and j = 1, then

$$l = (n_x - i)n_y n_z + (k - 1)n_y + j = 1$$

This corresponds to the upper left-hand corner of the estimation domain, at the furthest distance upstream of the rotor plane, as illustrated in Figure 4.

2. Measurement (MES) of the amplitude and of the direction of the wind at different measurement points

In a second stage, the LiDAR sensor carries out a measurement $m(t)$ relating to the wind speed at a measurement point (PM) situated upstream of the wind turbine 1. This measurement $m(t)$ corresponds to the signal received by the sensor originating from the measurement point (PM) in response to the signal emitted by the LiDAR sensor. Indeed, by interferometry and the Doppler effect, part of the Laser signal emitted by the LiDAR sensor is reflected by air molecules at the measurement point and also by aerosols (dust and microparticles in suspension). The measurement point is defined by the characteristics of the LiDAR sensor, notably the focal length, as well as by its orientation. This measurement, which is dependent on the wind speed, is a time and depends on the orientation of the LiDAR sensor.

For the case studied of the pulsed LiDAR, the measurements are obtained successively according to the mesh defined in the preceding step, starting with the longitudinal beam b0, then the oblique beam b1, up to the beam b4. An advantageous feature of this system is that it makes it possible to measure the projection of the wind speed at a plurality of distances simultaneously for a given beam. It is thus possible to obtain, for example, 10 successive distances between 50 m and 400 m, at a sampling rate of 0.25 Hz or of 1 Hz. It is of course possible to be limited to two measurements, which are sufficient to reconstruct a model in three dimensions. At each sampling time, only the measurements of the current beam selected are refreshed.

In a particular case, in accordance with Figure 4, the measurements are made at seven distances and notably at x = [50 80 120 160 200 240 280] m for the five beams. Thus, for each fixed plane x, the plane y-z is divided into cells as follows:

- The four first points (PM) correspond to the coordinates y-z of the measurement points for beams 1, 2, 3, 4 from the distance x = 280 m.
- The four second points (PM1) correspond to the coordinates y-z of the measurement points for beams 1, 2, 3, 4 from the distance x = 240 m.

- The four third points (PM2) correspond to the coordinates y-z of the measurement points for beams 1, 2, 3, 4 from the distance x = 200 m.
- The four fourth points (PM3) correspond to the coordinates y-z of the measurement points for beams 1, 2, 3, 4 from the distance x = 160 m.
- The four fifth points (PM4) correspond to the coordinates y-z of the measurement points for beams 1, 2, 3, 4 from the distance x = 120 m.
- The four sixth points (PM5) correspond to the coordinates y-z of the measurement points for beams 1, 2, 3, 4 from the distance x = 80 m.
- The four seventh points (PM6) correspond to the coordinates y-z of the measurement points for beams 1, 2, 3, 4 from the distance x = 50 m.
- The central point (PM7) corresponds to the coordinates y-z of the measurement points for beam 0 for all the distances.

The LiDAR measurements $m(k)$ for beams j = 0, 1, 2, 3, 4 at the distance x metres and at the instant k are given by the formula $mj,x(k)$ with j = 0, 1, 2, 3, 4.

For example, $m_{0,50}(1)$ is the LiDAR measurement for beam j = 0 at the distance x = 50 metres and at the instantaneous instant k = 1. In the context of the invention, the LiDAR measurement is then given by a formula of the type:

$$m_{j,x}(k) = a_j v_{j,x}(k) + b_j v_{j,y}(k) + c_j v_{j,z}(k)$$

in which $v_{j,x}(k)$, $v_{j,y}(k)$, $v_{j,z}(k)$ are values of the wind speed projected on a given reference frame at the initial time (k), and a_j, b_j, c_j, with j = 0, 1, 2, 3, 4, are measurement coefficients, which are given as,

$$\begin{cases} a_j = \cos(\theta_j), \\ b_j = \sin(\theta_j)\cos(\varphi_j), \\ c_j = \sin(\theta_j)\sin(\varphi_j) \end{cases}$$

in which θ_j, φj, with j = 0, 1, 2, 3, 4, are, respectively, the zenith and the azimuth of the measurement axis in a spherical coordinate system.

The advantage of defining the LiDAR measurement equation within the reference frame defined above, with the choice of spatial discretization chosen, is that it may be used directly, as the coordinates of the measurement point coincide with a particular point of the space discretized.

3. Estimation (EST) of the amplitude and of the direction of the wind at any instant (t) over all of the discretized points

This step consists in obtaining a value of the wind on the estimation points (PE) of the mesh.

To this end the estimation is made by means of optimization by a recursive least squares method weighted by a cost function which uses the measured data $m(k)$ of the LiDAR, but also spatial wind speed consistency data, temporal wind speed variation data, and data qualifying the quality of the measurements $m(k)$ of the LiDAR. This is what is explained below.

Taking into account temporal consistency makes it possible to quantify the “similarity” of the estimation of the wind field, at a date t, to the estimation of the wind field at a prior date (t-1, t-2, etc.).

The implementation of recursive least squares minimization weighted by the cost function, incorporating temporal consistency, corresponds to the implementation of an extended Kalman filter.

$$\omega(t) = \omega(t-1) + K(y(t) - C\omega(t-1))$$

The virtue of this approach is the capacity to consider an update of the estimation of the wind field at a date t, even if the measurements acquired at the date t are not valid or reliable, and to do so relying on the estimation of the wind field obtained at a prior date (t-1, t-2, etc.). Thus, by extension, the reconstruction of the wind field is robust against unavailability of data of the acquisition device, over a limited period of time linked to the temporal consistency limit of the estimation. A direct implementation of this solution is the putting in place of a buffer memory area, commonly called “buffer”, and containing the last valid measurements of each beam, at each distance from the LiDAR. This buffer is then the source of input data for the reconstruction algorithm.

For example, for a 4-beam pulsed device, acquiring over 10 distances, the buffer will have 4*10 places, where the 40 last valid radial measurements acquired will be stored. Thus, indicators such as the spatial average of the wind speed at a given distance will be stabilized and made reliable by the availability, at each acquisition date, of all of the measurements, be they current, delayed or estimated. Indeed, it proves that not considering all of the beams in order to establish a spatial indicator of the wind results in erroneous values for spatial averages, in particular when the wind is subject to shear, or when the acquisition device is misaligned with respect to the prevailing direction of the wind.

It is also necessary to include a dating or an indicator of the obsolescence of the data stored, in order to be able to determine their relevance as a source of information for updating the estimation of the wind field. This relevance depends on the temporal consistency of the phenomenon estimated, namely the wind field propagating towards the wind turbine where the LiDAR is positioned. The temporal consistency of the wind may be an adjustment parameter, or result from a wind model.

Robust use of the approach described in the patent requires a confidence interval or index, accompanying the estimation of the wind field and its associated descriptive quantities, to be supplied at each instant. The descriptive quantities of the wind field may be, for example: the horizontal and vertical shear of the amplitude and of the direction, the average speed and direction at each measurement distance, the intensity of the turbulence, etc.

This confidence interval is constructed from an equation taking into account:

- The number of measurements which are valid at the current acquisition date
- The dating of the last valid measurements, if the last acquisitions obtained are not all reliable
- The confidence interval which is intrinsic to the reconstruction algorithm. This confidence interval depends on the variance deduced from the estimation process. In the case of implementation by a Kalman filter, this may be the values of the covariance matrix of the process modelled.

These considerations make it possible to robustly and reliably synthesize an uncertainty to be associated with the reconstruction of the wind field, which incorporates the availability and the obsolescence of the measurements with the intrinsic confidence index of the estimator.

This uncertainty may be supplied with the measurement, and assimilated to the overall standard deviation of the estimation. This quantity is very relevant information for uses of the reconstruction in a context of real-time diagnosis, or of LiDAR-assisted control of a wind turbine.

3.1 Spatial differences

These subsections aim to define the spatial wind consistency data in the context of the invention and more particularly in the context of a LiDAR mounted on the nacelle 3 of a wind turbine 1.

In this step, the components of the wind speed on the axes x, y and z of the reference frame defined above are considered.

During this estimation step, it is accepted that the wind speed changes relatively little in the space, and that the wind has high spatial consistency in a small volume of the space. The following exposition is given here for the components v_x, that is to say for the first n variables of ω with an estimation domain shown in Figure 4 (the approach is similar for the components v_y and v_z) and taking $n_x = n_y = n_z = 3$.

3.1.1 Longitudinal difference

The longitudinal difference corresponds to the change in v_x along the axis x, and this changes gently according to the invention. In this case the partial derivative dv_x/dx is relatively small. In other terms,

$$\begin{cases} \omega_1 - \omega_{10} \approx 0 \\ \omega_2 - \omega_{11} \approx 0 \\ \vdots \\ \omega_{18} - \omega_{27} \approx 0 \end{cases}$$

The preceding equation may be written in a compact vector form as:

$$C_{x1}\omega \approx 0$$

in which

$$C_{x1} = \begin{bmatrix} +1 & 0 & \dots & 0 & -1 & 0 & \dots & 0 \\ 0 & +1 & \dots & 0 & 0 & -1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & +1 & 0 & 0 & \dots & -1 \end{bmatrix}$$

It should be noted that each row of C_{x1} contains a +1 and a -1.

Similarly, the variation of v_y and v_z may be calculated along the longitudinal axis as:

$$\begin{cases} C_{y1}\omega \approx 0, \\ C_{z1}\omega \approx 0 \end{cases}$$

in which C_{x1}, C_{z1} are coefficient matrices, which contain only one +1 and one -1 in each row.

By defining:

$$C_1 = \begin{bmatrix} C_{x1} \\ C_{y1} \\ C_{z1} \end{bmatrix}$$

the equation:

$$C_1\omega \approx 0$$

is obtained, which characterizes the variation of the wind speed for the estimation domain along the longitudinal axis.

3.1.2 Lateral difference

The lateral difference is the change in v_x along the axis y. Similarly, as the wind changes smoothly, the partial derivative dv_x/dy is relatively small. In other terms,

$$\begin{cases} \omega_1 - \omega_2 \approx 0 \\ \omega_2 - \omega_3 \approx 0 \\ \vdots \\ \omega_{38} - \omega_{37} \approx 0 \end{cases}$$

The preceding equation may be written in a compact vector form as

$$C_{xt}\omega \approx 0$$

in which

$$C_{xt} = \begin{bmatrix} +1 & -1 & 0 & \dots & 0 & 0 & 0 & \dots & 0 & 0 \\ 0 & +1 & -1 & \dots & 0 & 0 & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 & \dots & +1 & -1 \end{bmatrix}$$

Each row of C_{xt} contains a +1 and a -1.

Similarly, the variation of v_y and v_z along the lateral axis may be calculated as

$$\begin{cases} C_{yt}\omega \approx 0, \\ C_{zt}\omega \approx 0 \end{cases}$$

in which C_{yt}, C_{zt} are coefficient matrices which contain only one +1 and one -1 for each row.

By defining:

$$C_t = \begin{bmatrix} C_{xt} \\ C_{yt} \\ C_{zt} \end{bmatrix}$$

it is clear that the equation:

$$C_t\omega \approx 0$$

characterizes the variation of the wind speed for the estimation domain along the lateral axis.

<u>3.1.3 Vertical difference</u>

The vertical profile of the wind speed is given by a power law, this making it possible to obtain a description of the wind speed component v_x at different heights which is much more precise.

The vertical profile of the wind speed describes the evolution of the longitudinal wind speed as a function of the altitude relative to the ground. The power law of the profile of the wind speed is generally used to estimate the longitudinal wind speed v_l at an altitude z above the ground, taking into account the longitudinal wind speed v_{lr} at a reference altitude z_r, using the equation,

$$v_l = v_{lr}\left(\frac{z}{z_r}\right)^{\alpha}$$

in which alpha is the exponent of the power law, which is generally specified as a function of stability.

The constant value alpha = 1/7 is commonly used, consistently with a hypothesis of relatively low wind shear. However, it must be noted that considering alpha to be constant amounts to abstracting away from the roughness of the surface of the ground, from the interactions of the wind with possible obstacles, and from the stability of the atmosphere.

Using this power law, a vertical difference of the wind is thus obtained, given by:

$$\begin{cases} \omega_1 - \left(\frac{z_1}{z_4}\right)^{\alpha}\omega_4 \approx 0 \\ \omega_2 - \left(\frac{z_2}{z_5}\right)^{\alpha}\omega_5 \approx 0 \\ \vdots \\ \omega_{33} - \left(\frac{z_{33}}{z_{36}}\right)^{\alpha}\omega_{36} \approx 0 \end{cases}$$

in which z_j is the height of ω, and α is the exponent of the power law, which is assumed to be 1/7.

The preceding equation may be written in a compact vector form as:

$$C_{zv}\omega \approx 0$$

in which

$$C_{zv} = \begin{bmatrix} +1 & 0 & 0 & -\left(\frac{z_1}{z_4}\right)^{\alpha} & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 & -\left(\frac{z_2}{z_5}\right)^{\alpha} & 0 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & +1 & 0 & 0 & -\left(\frac{z_{33}}{z_{36}}\right)^{\alpha} \end{bmatrix}$$

Similarly, the variation of v_y and v_z along the vertical axis may be quantified as

$$\begin{cases} C_{yv}\omega \approx 0, \\ C_{zv}\omega \approx 0 \end{cases}$$

However, as the power law of the profile of the wind applies only to the longitudinal wind speed, C_{yv}, C_{zv} contain only one +1 and one -1 for each row.

By defining:

$$C_v = \begin{bmatrix} C_{xv} \\ C_{yv} \\ C_{zv} \end{bmatrix}$$

the equation:

$$C_v\omega \approx 0$$

is obtained, which characterizes the variation of the wind speed for the estimation domain along the vertical axis.

Finally, using:

$$C_t\omega \approx 0$$

and

$$C_l\omega \approx 0$$

the following is obtained:

$$\begin{cases} C_t\omega \approx 0, \\ C_l\omega \approx 0, \\ C_v\omega \approx 0 \end{cases}$$

or, equivalently,

$$C_s\omega \approx 0$$

which is the equation which characterizes the variation of the total wind speed along the axes x, y and z.

With:

$$C_s = \begin{bmatrix} C_t \\ C_l \\ C_v \end{bmatrix}$$

3.2 LiDAR measurements

For the requirements of the calculation, it is important to rewrite the measurement equation in vector form *w*. In the preceding example of a five-beam LiDAR and for seven measurements per beam, j = 0, 1, 2, 3, 4 and x = [50, 80, 120, 160, 200, 240, 280] are obtained,

$$\begin{cases} v_{j,x} = [0 \ \dots \ 0 \ 1 \ 0 \ \dots \ 0]\omega = C_{j,xx}\omega \\ v_{j,y} = [0 \ \dots \ 0 \ 1 \ 0 \ \dots \ 0]\omega = C_{j,xy}\omega \\ v_{j,z} = [0 \ \dots \ 0 \ 1 \ 0 \ \dots \ 0]\omega = C_{j,xz}\omega \end{cases}$$

By combining with:

$$m_{j,x}(k) = a_j v_{j,x}(k) + b_j v_{j,y}(k) + c_j v_{j,z}(k)$$

the following is obtained,

$$m_{j,x} = C_{j,x}\omega$$

in which

$$C_{j,x} = [a_j \ b_j \ c_j]\begin{bmatrix} C_{j,xx} \\ C_{j,xy} \\ C_{j,xz} \end{bmatrix}$$

which may be rewritten in a compact vector form:

$$C_m\omega = m_m$$

in which

$$m_m = \begin{bmatrix} m_{0,50} \\ m_{1,50} \\ \vdots \\ m_{4,280} \end{bmatrix}, \ C_m = \begin{bmatrix} C_{0,50} \\ C_{1,50} \\ \vdots \\ C_{4,280} \end{bmatrix}$$

In order to take into account the measurement noises, a more realistic model for the Lidar measurements may be introduced as follows,

$$C_m\omega = m_m + \varepsilon_m$$

in which ε_m describes the measurement noises.

3.3 The weighted recursive least squares method

It is accepted that the wind speed changes little not only in the space, but also in time. Below, a means for taking into account this information in the optimization approach is supplied. $\hat{\omega}(0)$ is the estimation of the wind speed at the time 0. At each instant, the optimization problem is the following:

$$\min_{\omega(t)} J(t)$$

with

$$J(t) = (\omega(0) - \hat{\omega}(0))^T P_0^{-1}(\omega(0) - \hat{\omega}(0)) + \sum_{j=1}^{t} (\omega(j) - \omega(j-1))^T Q^{-1} (\omega(j) - \omega(j-1)) + \\ + \sum_{j=1}^{t} \omega(j)^T C_s^T R_s^{-1} C_s \omega(j) + \sum_{j=1}^{t} (C_m\omega(j) - m_m)^T R_m^{-1} (C_m\omega(j) - m_m(j))$$

There are four terms in the preceding cost function.

- The first term penalizes knowledge of the initial wind speed $\omega(0)$.

- The second term penalizes variation of the wind speed in time.
- The third term penalizes variation of the wind speed in the space.
- The fourth term penalizes Lidar measurement quality.

Using the preceding formula, a clear interpretation of the weighting matrices P_0, Q, R_s and R_m may be obtained. Thus:

- If the wind speed $\omega(t)$ at the time t = 0 is indeed known, then $\omega(0) = \hat{\omega}(0)$, then P_0 is small. Otherwise P_0 is large.
- If there are many variations of the wind speed in time, then Q is large. Otherwise Q is small.
- If the wind speed changes rapidly, then R_s is large. Otherwise R_s is small.
- If there are many measurement noises in the Lidar measurements, then R_m is large. If not, R_m is small.

In the case in which the following three limiting cases are considered:

- No information on the initial wind speed is available. Consequently P_0 is very large. The term:

$$(\omega(0) - \hat{\omega}(0))^T P_0^{-1} (\omega(0) - \hat{\omega}(0))$$

may thus be ignored in the cost function.

- There is no relationship between the wind speed at the instant t and the wind speed at the instant t-1. In this case, Q may be chosen to be very large. The following term may be ignored:

$$\sum_{j=1}^{t} (\omega(j) - \omega(j-1))^T Q^{-1} (\omega(j) - \omega(j-1))$$

- The variation of the wind speed in the space is very low. In this case, R_s may be taken to be very small. The following term is important in the cost function:

$$\sum_{j=1}^{t} \omega(j)^T C_s^T R_s^{-1} C_s \omega(j)$$

The following is defined:

$$C = \begin{bmatrix} C_s \\ C_m \end{bmatrix}, \; R = \begin{bmatrix} R_s & 0 \\ 0 & R_m \end{bmatrix}$$

The weighted recursive least squares method used to solve the optimization problem presents itself in the following way:

- The optimization variables are initialized in the following manner:

$$\begin{cases} \omega(0) = \hat{\omega}(0), \\ P(0) = P_0 \end{cases}$$

- At each instant t:

▪ The following is defined:

$$y(t) = \begin{bmatrix} 0 \\ y_m(t) \end{bmatrix}$$

in which 0 is a zero vector of appropriate dimension.

▪ An auxiliary matrix *K* is calculated such that

$$K = (P(t-1)+Q)C(C^T(P(t-1)+Q)C+R)^{-1}$$

▪ The matrix *P(t)* is calculated such that

$$P(t) = (I-KC)P(t-1)$$

in which *I* is an identity matrix of appropriate dimension.

▪ The wind speed at the instant t is then estimated thus:

$$\omega(t) = \omega(t-1) + K(y(t) - C\omega(t-1))$$

4. Reconstruction of the incident wind field in three dimensions (3D) and in real time

In this step, a processor incorporated into the LiDAR sensor retrieves all of the data on the amplitude and direction of the wind which were measured and estimated during the preceding steps. These data are retrieved in real time for each measurement point (PM) and estimation point (PE) defined above. Thus the LiDAR sensor is able to reconstruct all of the incident wind field on the LiDAR, as may be seen in Figure 5.

In the same Figure 5, a reconstructed wind field is shown for a time at 68 seconds. On the vertical axis the altitude relative to the ground (in m) is shown and on the horizontal axis the distance to the nacelle (in m) and the lateral positions relative to the LiDAR (in m) are shown.

The invention relates secondly to a method for controlling and/or monitoring a wind turbine equipped with a LiDAR sensor as described above and an afferent driving logic controller 10, which comprises the following steps:

i) A step of generation of a strategy of feedforward control (CON) of said wind turbine 1 by using the reconstruction of the incident wind field in three dimensions and in real time obtained by the method according to the invention,

ii) A driving step (PIL) incorporating the control strategy generated which consists notably in driving the pitch of the blades 7 or the orientation of the nacelle 3.

Figure 6 shows the overall operation of such a wind turbine 1. The wind turbine 1 comprises to this end a LiDAR sensor 2 which is in accordance with the invention, and its processing unit, a computer device comprising a software solution for 3D reconstruction of the wind field, a driving logic controller incorporating the control strategy and a device for driving the blades and/or the nacelle of the wind turbine. In connection with Figure 6, the invention applied to a wind turbine operates in the following manner:

- Firstly, the LiDAR performs the step of acquiring and modelling the incident wind field as described above so as to reconstruct a 3D incident wind field (steps ME, MA, EST, MOD 3D of Figure 6),
- Secondly, the driving logic controller 10 generates the control strategy (CON) and drives (PIL) the members of the wind turbine 1, taking into account the control strategy generated.

This method according to the invention makes it possible to analyse, in real time, the incident wind or detect gusts, power curves and intensities of the turbulence, this possibly serving to regulate or supervise the wind turbine so as to obtain a better alignment of the wind turbine, this leading to optimization of production and minimization of the loads and of the wear.

Patentkrav

1. Fremgangsmåde til registrering og modellering ved hjælp af en LiDAR-sensor af et indfaldende vindfelt i et rum, der befinder sig opstrøms for LiDAR-sensoren, kendetegnet ved, at fremgangsmåden omfatter:

a) et trin med maskeinddeling (MA) af det rum, der befinder sig opstrøms for LiDAR-sensoren, hvor maskeinddelingen af rummet udføres ved hjælp af et sæt af diskretiserede punkter, der placeres i overensstemmelse med et forud fastlagt tredimensionalt gitter, der omfatter et sæt masker bestående af estimeringspunkter og målepunkter (PM)

b) et trin med måling (MES) af vindens amplitude og retning i de forskellige målepunkter (PM), der befinder sig i rummet opstrøms, og som placeres i mindst to adskilte afstande fra LiDAR-sensoren langs mindst tre måleakser

c) et trin til estimering (EST) af vindens amplitude og retning på et hvilket som helst tidspunkt (t) over alle estimeringspunkterne, og estimeringen udføres ved optimering ved hjælp af en metode med vægtede rekursive mindste kvadrater af en omkostningsfunktion $J(t)$, der i det mindste anvender dataene fra målepunkterne (PM), rumlige kohærensdata for vindhastigheden, tidsmæssige kohærensdata for vindhastighed såvel som data, der kvalificerer kvaliteten af de målinger, der er blevet udført i målepunkterne, og omkostningsfunktionen $J(t)$ på et hvilket som helst tidspunkt (t) skrives i følgende form:

$$J(t) = (\omega(0) - \hat{\omega}(0))^T P_0^{-1} (\omega(0) - \hat{\omega}(0)) + \sum_{j=1}^{t} (\omega(j) - \omega(j-1))^T Q^{-1} (\omega(j) - \omega(j-1)) + \\ + \sum_{j=1}^{t} \omega(j)^T C_s^T R_s^{-1} C_s \omega(j) + \sum_{j=1}^{t} (C_m \omega(j) - m_m)^T R_m^{-1} (C_m \omega(j) - m_m(j))$$

hvor ω er en ordnet vektor, der er sammensat af alle komponenterne af hastigheden i de punkter i rummet, hvor vinden estimeres, ω^(0) er estimatet af vindhastigheden på tidspunktet 0, P_0, Q, R_s et R_m er vægtningsmatricer af passende størrelse, og C_s, C_m er matricer, der tager højde for vindhastigheden og målestøjen

d) et trin til rekonstruktion (MOD 3D) i realtid og i en defineret ramme af det indfaldende vindfelt i tre dimensioner

(3D) ud fra de amplituder og retninger af vinden, der estimeres og måles for hvert punkt i masken (MA).

2. Fremgangsmåde ifølge krav 1, kendetegnet ved, at målingen m af vindens amplitude og retning i et målepunkt (PM) angives ved en relation af formen:

$$m_{j,x}(k) = a_j v_{j,x}(k) + b_j v_{j,y}(k) + c_j v_{j,z}(k)$$

hvor $v_{j,x}(k)$, $v_{j,y}(k)$, $v_{j,z}(k)$ er værdier af vindhastigheden, der projiceres på en given referenceramme på starttidspunktet (k), og a_j, b_j, c_j med j = 0, 1, 2, 3, 4 er målekoefficienter, der angives som

$$\begin{cases} a_j = \cos(\theta_j), \\ b_j = \sin(\theta_j)\cos(\varphi_j), \\ c_j = \sin(\theta_j)\sin(\varphi_j) \end{cases}$$

hvor θj, ϕj, j = 0, 1, 2, 3, 4 henholdsvis er måleaksens zenit og azimut i et sfærisk koordinatsystem.

3. Fremgangsmåde ifølge et af de foregående krav, kendetegnet ved, at målingerne af vindens amplitude og retning i de forskellige målepunkter (PM) udføres med en samplingshastighed på mindst 0,25 Hz.

4. Fremgangsmåde ifølge et af de foregående krav, kendetegnet ved, at målingerne af vindens amplitude og retning i de forskellige målepunkter (PM) udføres i mindst to forskellige afstande langs måleaksen.

5. Fremgangsmåde ifølge et af de foregående krav, kendetegnet ved, at målingerne af vindens amplitude og retning udføres langs mindst tre måleakser.

6. Fremgangsmåde ifølge et af de foregående krav, kendetegnet ved, at vindhastighedens rumlige kohærens langs x-, y- og z-akserne i et kartesisk koordinatsystem estimeres ved hjælp af en formel af typen:

$$C_s \omega \approx 0$$

med

$$C_s = \begin{bmatrix} C_l \\ C_t \\ C_v \end{bmatrix}$$

hvor:

- C_l karakteriserer vindhastighedens ændring for et estimeringsdomæne langs den langsgående akse x, og
- C_t karakteriserer vindhastighedens ændring for et estimeringsdomæne langs den tværgående akse y, og
- C_v karakteriserer vindhastighedens ændring for et estimeringsdomæne langs den lodrette akse z, og
- vektoren ω er en ordnet vektor, der er sammensat af alle komponenterne af vindhastigheden i de punkter i rummet, hvor vinden estimeres.

7. Fremgangsmåde ifølge det foregående krav, kendetegnet ved, at den rumlige kohærens af vindhastighedens rumlige kohærens langs akserne x, y og z i det kartesiske koordinatsystem estimeres med følgende hypoteser:

o ændringen af vindhastigheden langs længdeaksen x er lille, og den partielle afledte dv_x/dx er relativt lille langs længdeaksen

o vinden skifter uden stød langs den tværgående akse y, og den partielle afledte dv_x/dy er lille langs den tværgående y-akse

o vinden ændrer sig med en effektlov langs den lodrette akse z, som er givet ved:

$$v_l = v_{lr}\left(\frac{z}{z_r}\right)^{\alpha}$$

hvor alfa er en eksponent for effektloven, v_l er den langsgående vind i en højde z over jorden, og z_r er en referencehøjde.

8. Fremgangsmåde ifølge et af de foregående krav, kendetegnet ved, at kvaliteten af de målinger, der udføres af LiDAR-sensoren, angives ved en model med formen:

$$C_m\omega = m_m + \epsilon_m$$

hvor $\in_m$ beskriver målestøjen.

9. Fremgangsmåde ifølge et af de foregående krav, kendetegnet ved, at estimeringen af vindfeltets amplituder og retninger på et tidspunkt (t) over alle estimeringspunkterne angives ved følgende formel:

$$\omega(t) = \omega(t-1) + K(y(t) - C\omega(t-1))$$

hvor *K* betegner en hjælpematrix og *C* er en matrix, der defineres ved:

$$C = \begin{bmatrix} C_s \\ C_m \end{bmatrix}$$

10. Computerprogramprodukt, kendetegnet ved, at det omfatter kodeinstruktioner, som er beregnet til at implementere trinnene i en fremgangsmåde til registrering og modellering ved hjælp af en LiDAR-sensor af et indfaldende vindfelt ifølge et af de foregående krav, når programmet udføres på en behandlingsenhed i LiDAR-sensoren.

11. LiDAR-sensor, kendetegnet ved, at den i hukommelsen omfatter kodeinstruktionerne for et computerprogramprodukt ifølge det foregående krav og beregnet til at køre et sådant computerprogramprodukt.

12. Vindmølle 1, kendetegnet ved, at vindmøllen 1 omfatter en LiDAR-sensor 2 ifølge det foregående krav.

13. Vindmølle 1 ifølge det foregående krav, kendetegnet ved, at LiDAR-sensoren er anbragt på vindmøllens gondol.

14. Fremgangsmåde til styring og/eller overvågning af en vindmølle 1, der er udstyret med en LiDAR-sensor 2 og en styreautomat, kendetegnet ved, at følgende trin udføres:
i) et trin til udvikling af en kontrolstrategi (CON) ved foregribelse af vindmøllen ved at udnytte den rekonstruktion af det indfaldende vindfelt i tre dimensioner og i realtid, som er opnået ved hjælp af fremgangsmåden til registrering og modellering ved hjælp af en LiDAR-sensor af et indfaldende vindfelt ifølge et af kravene 1 til 10
ii) et styringstrin (PIL), der omfatter den udviklede kontrolstrategi, som består i at styre vinklen på bladene 7 eller orienteringen af en gondol 3.

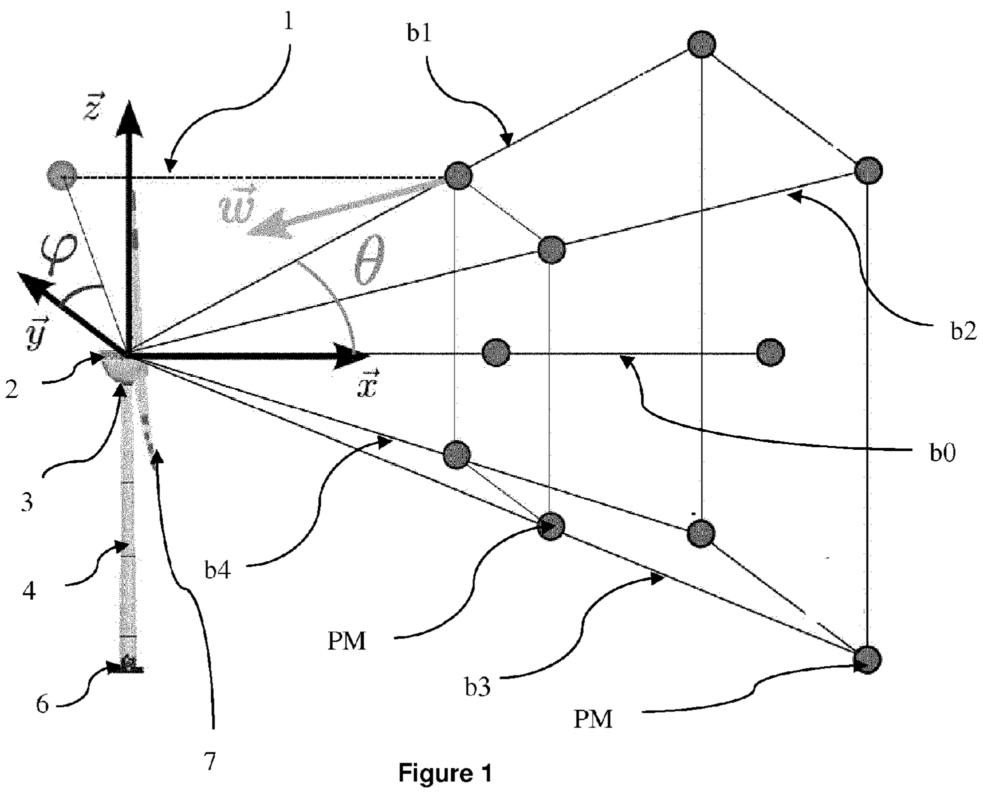

Figure 1

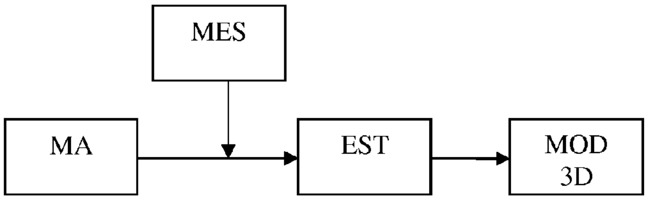

Figure 2

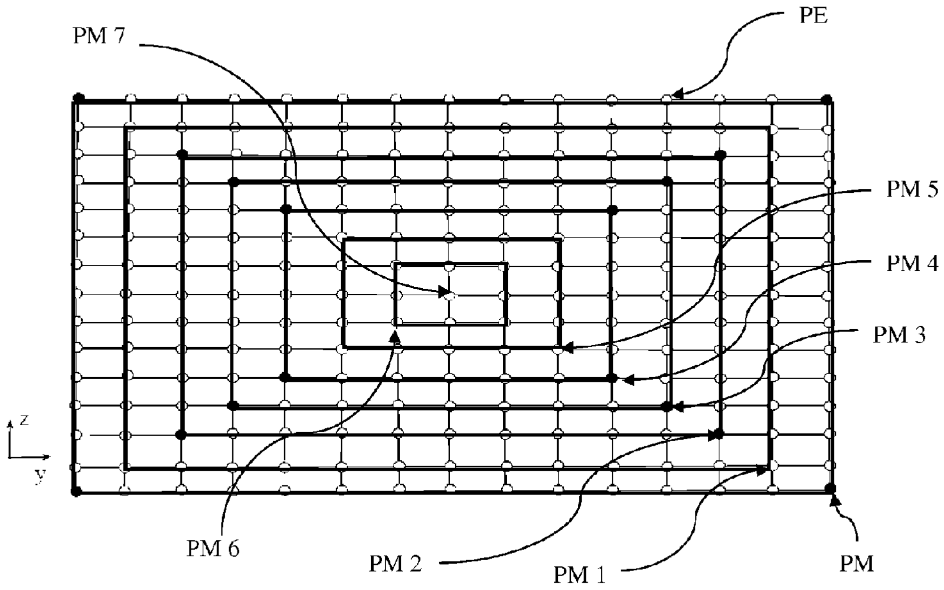

Figure 3

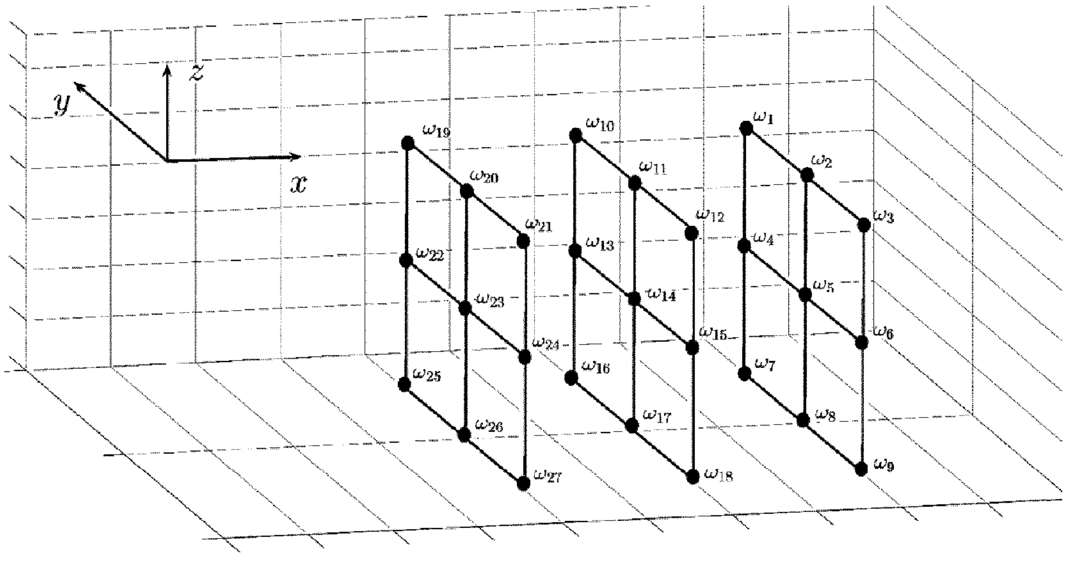

Figure 4

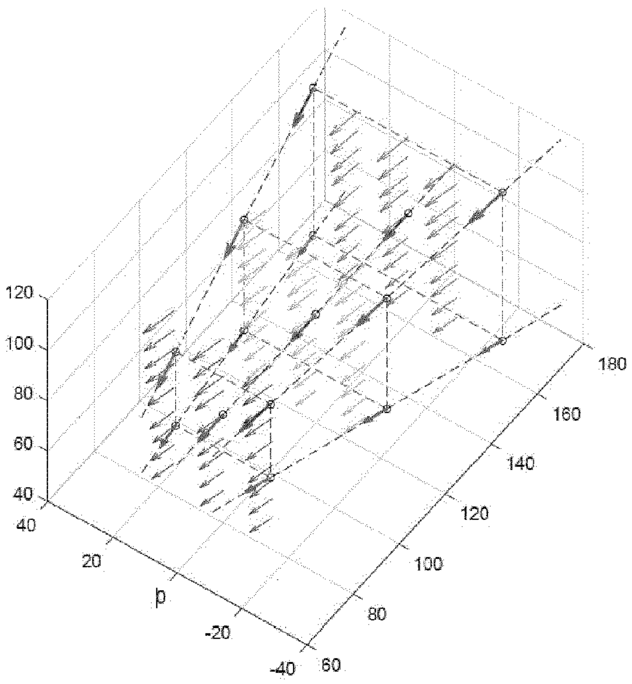

Figure 5

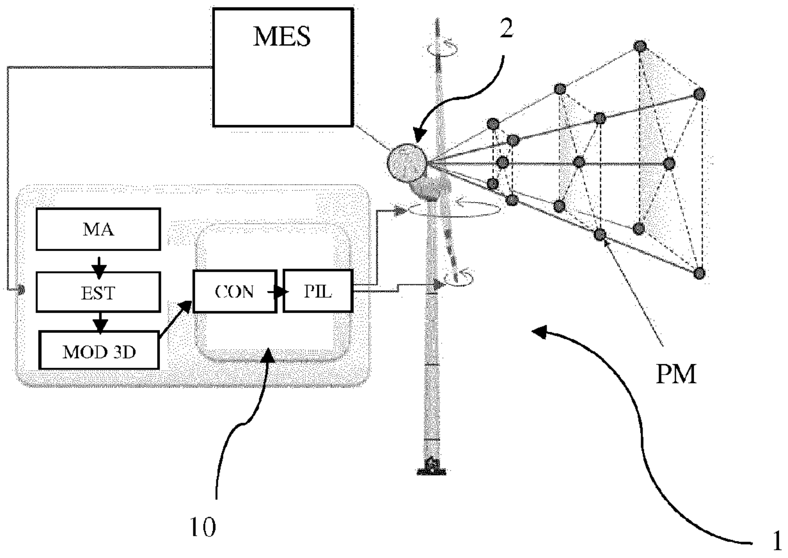

Figure 6