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Description

Technical field

5 The present invention relates to the field of determining wind speed components, notably in order to assess the opportunity of installing a wind turbine on a site (location).

10 Prior to installing a wind turbine or a wind farm, the wind potential on this site needs to be assessed. Indeed, the size of the wind turbine, its class and its structure depend on wind characteristics, such as the mean wind speed, the maximum wind speed, the wind turbulence intensity (which corresponds to the ratio of the wind speed standard deviation to the mean wind
15 speed), etc. For example, the size of the wind turbine can be selected according to the mean wind speed distribution, and the wind turbine class can be selected according to the turbulence intensity. Given that changing from one wind turbine class to another involves a significant cost, it is important that the
20 wind characteristics are well known prior to installing a wind turbine.

In addition, determining wind speed components is particularly critical as it also allows the energy-producing resource to be
25 known. This is important for wind energy projects, since this also affects the financial viability of the wind turbine installation project.

Prior art

30 In order to carry out these measurements, the conventional technique involves installing a measurement mast on the measurement site (which is a site that is considered for implementing a wind turbine). Such a measurement mast is
35 equipped with a significant number of sensors and it requires a specific installation involving a significant cost and is not easy to move from one site to another due to its dimensions. According to a second technique, a LiDAR (Light Detection And

Ranging) sensor can be used. LiDAR is remote sensing or optical measurement technology based on analysing the properties of a beam returned to its emitter. This method is notably used for determining the distance to an object by means of a pulsed laser.

5 Unlike radar based on a similar principle, the LiDAR sensor uses visible or infrared light instead of radio waves.

In the field of wind turbines, the LiDAR sensor is heralded as being an essential sensor for the correct operation of large
10 wind turbines, especially now that their size and power is increasing (currently 5 MW, yet soon 12 MW for offshore turbines). This sensor allows remote wind measurements to be carried out, initially allowing the wind turbines to be calibrated so that they can deliver maximum power (power curve
15 optimisation). For this calibration step, the LiDAR sensor can be positioned on the ground and oriented vertically (profiler), which allows the wind speed and its direction to be measured, as well as the wind gradient depending on the altitudes. This technique can be referred to as ground-based LiDAR.

20

This technique is notably described in patent applications EP 3287810 and US 2019/293836.

The measuring principle of LiDAR sensors is based on a wind
25 homogeneity hypothesis at each altitude. Indeed, LiDAR sensors are made up of several laser beams with different orientations, which in turn measure the projection of the wind on the beams at several altitudes.

30 These radial measurements are then combined so as to reconstruct a mean wind measurement at each altitude, assuming that the instantaneous wind is identical at any measurement point of the LiDAR sensor.

35 This hypothesis is even more important when dealing with a complex site where local wind speed variations significantly affect the accuracy of the LiDAR measurement thus obtained.

Figure 1 schematically shows, by way of a non-limiting example, a ground-based and vertically oriented LiDAR sensor 1 for determining wind speed components. The LiDAR sensor 1 is used to obtain at least one measurement signal on at least one measurement plane PM (only two measurement planes are shown). The x-, y- and z- axes are also shown in this figure. The reference point of this coordinate system is the centre of the LiDAR sensor. The direction x is a horizontal direction. The direction y, perpendicular to the direction x, is a second horizontal direction (the directions x, y form a horizontal plane). The direction z is the vertical direction (corresponding to the measurement direction of the LiDAR sensor 1) pointing upwards, the z-axis is perpendicular to the x- and y-axes. The measurement planes PM are planes formed by the directions x, y at a distance from the LiDAR sensor 1 (for a non-zero value of z). The measurement planes PM are parallel to one another.

As shown in figure 1, which is an embodiment of a pulsed LiDAR sensor, the LiDAR sensor 1 that is used comprises four beams or measurement axes 2. The measurement beams 2 are inclined relative to the vertical z-axis. The LiDAR sensor carries out a punctual measurement at each measurement point (b1, b2, b3, b4), which are intersection points of a measurement plane PM and a beam 2. These measurement points (b1, b2, b3, b4) are represented by black circles in figure 1.

This figure also shows, only at point b1, the wind speed vector W, and these three components W_x , W_y , W_z on the x-, y- and z-axes, respectively.

30

Figure 2 schematically shows a top view of the measurement points (b1, b2, b3, b4) in the measurement plane PM, located at an altitude relative to a LiDAR sensor with 4 beams. The hypothesis that is then formed in the conventional measurement method involves assuming that the three wind components at the measurement points b1 to b4 are equal at a given time, in other words, that the wind is homogeneous in the grey square whose vertices correspond to the measurement points (b1, b2, b3, b4).

35

This homogeneity hypothesis in the measurement plane is not realistic, especially since the measurement plane is far away from the ground-based LiDAR sensor. For example, for a LiDAR sensor with four beams, as illustrated in figures 1 and 2, for a measurement plane located 150 m away from the LiDAR sensor, and for a 28° aperture of the measurement beams, the surface area of the square delimited by the measurement points is 12,700 m². It seems obvious that the wind speed is not homogeneous over such a surface area. Thus, this method of the prior art does not allow the wind speed components to be accurately determined.

Summary of the invention

The aim of the present invention is to determine the wind speed components in an accurate, robust, reliable and inexpensive manner. To this end, the invention relates to a method for determining wind speed components by means of a ground-based LiDAR sensor. This method involves determining the wind direction and the mean wind speed in a measurement plane, then constructing a projection line perpendicular to the wind direction in the measurement plane, and then determining a time offset between the measurement points and the projection line, so as to determine corrected measurement signals. These corrected measurement signals allow the wind speed components in the measurement plane to be determined.

The invention relates to a method for determining wind speed components by way of a LiDAR sensor, said LiDAR sensor being oriented substantially vertically in order to carry out the measurements in at least one substantially horizontal measurement plane, each measurement plane comprising at least two measurement points. The following steps are implemented for this method:

- a) acquiring measurement signals from said LiDAR sensor for each measurement point of said at least one measurement plane;
- b) determining the mean wind direction and the mean wind speed in said at least one measurement plane by way of a reconstruction

of the wind based on said measurement signals;

c) constructing a projection line perpendicular to said determined wind direction in said at least one measurement plane;

5 d) determining a time offset between each measurement point of said at least one measurement plane and said constructed projection line, by way of said determined mean wind speed;

e) determining, for each measurement point of said at least one measurement plane, a corrected measurement signal, said
10 corrected measurement signal corresponding to the measurement signal at a time preceding the time under consideration minus a duration corresponding to said time offset; and

f) determining said wind speed components in said at least one measurement plane by way of said corrected measurement signals.

15

According to one embodiment, said projection line is constructed by a line perpendicular to said wind direction that passes through the barycentre of said measurement points of said at least one measurement plane, or that passes through a
20 measurement point of said at least one measurement plane.

Advantageously, said projection line is constructed by a line perpendicular to said wind direction that passes through the measurement point of said at least one measurement plane having
25 the most recent measurement.

According to one implementation, said reconstruction of the wind takes into account a hypothesis of the wind being uniform in said at least one measurement plane.

30

According to one aspect, said time offset δt of the measurement point i is determined using the following formula:

$$\delta t_i = \frac{x_i \cos \Psi - y_i \sin \Psi}{\bar{v}}$$

where x_i and y_i are the coordinates of said measurement point i
35 in the coordinate system associated with said at least one measurement plane, $\bar{v}$ is said determined mean wind speed, and Ψ is the angle formed between the y -axis of said at least one measurement plane and said projection line.

According to one feature, said corrected measurement signal is determined by interpolating said measurement signals before and after said measurement point in question.

5

Advantageously, said wind speed components are determined by way of the following equation:

$$\begin{pmatrix} w_x(t) \\ w_y(t) \\ w_z(t) \end{pmatrix} = L_1^{N+} \begin{pmatrix} m_1(t - \delta t_1) \\ m_2(t - \delta t_2) \\ \vdots \\ m_N(t - \delta t_N) \end{pmatrix}$$

where w_x , w_y , w_z are the wind speed components, m_1 , m_2 , ..., m_N are the measurement signals from the measurement points 1 to N , δt is said time offset of the measurement points 1 to N , and L_1^{N+} is a matrix for geometrically reconstructing the wind speed components.

15 According to one embodiment, said mean wind direction and said mean wind speed are determined for a fixed duration or for a sliding time window, said fixed duration or said sliding time window preferably ranging between 1 min and 1 h, and preferentially between 5 min and 30 min.

20

According to one implementation, said mean wind speed is determined in said at least one measurement plane by way of a frozen turbulence hypothesis, and considering the vertical component of the wind speed to be zero.

25

List of figures

Further features and advantages of the method according to the invention will become apparent upon reading the following description of non-limiting embodiments, with reference to the appended figures, in which:

30

- Figure 1, already described, illustrates a ground-based LiDAR sensor for a method for determining wind speed components;

- Figure 2, already described, illustrates a measurement plane of a ground-based LiDAR sensor;

35

- Figure 3 illustrates the steps of the method according to one embodiment of the invention;
- Figure 4 illustrates the offset of the measurement points of a measurement plane on the projection line according to a first
5 embodiment of the invention;
- Figure 5 illustrates the offset of the measurement points of a measurement plane on the projection line according to a second embodiment of the invention;
- Figure 6 illustrates a geometric parametrisation of the beams
10 of a LiDAR sensor for a measurement plane;
- Figure 7 illustrates a measurement plane of a LiDAR sensor with nine beams by way of an example; and
- Figure 8 illustrates radial speed measurements of beams 5 and 7 in the example of figure 7 used for a method according to the
15 prior art and for the method according to one embodiment of the invention.

Description of the embodiments

- 20 The present invention relates to a method for determining wind speed components by means of a LiDAR sensor. Wind speed components refer to the projections of the wind speed in a fixed coordinate system, notably in an orthonormal coordinate system.
- 25 For the invention, the LiDAR sensor is oriented substantially vertically, in other words, the measurement is oriented along a substantially vertical axis. For example, the LiDAR sensor can be placed on the ground and oriented vertically. According to the invention, the LiDAR sensor allows the wind speed to be
30 measured over at least one measurement plane. Given the orientation of the LiDAR sensor, each measurement plane is substantially horizontal. Several types of LiDAR sensor exist, for example, scanning LiDAR sensors, continuous wave LiDAR sensors or pulsed LiDAR sensors. Within the scope of the
35 invention, a pulsed LiDAR sensor is preferably used. However, the other LiDAR technologies also can be used while remaining within the scope of the invention.

The LiDAR sensor allows continuous measurement. Consequently, using such a sensor allows measurement signals to be continuously determined. Furthermore, the LiDAR sensor can be easy to move from one site to another. For example, the sampling
5 rate of the LiDAR sensor can range between 0.1 and 5 Hz (or more in the future), and it can be 1 Hz. In addition, the LiDAR sensor allows relative information to be obtained in several measurement planes at various heights. Consequently, the LiDAR sensor also can be used for determining wind speed components
10 at various heights, which can notably help to determine the wind speed variation according to the height.

The LiDAR sensor implemented in the method according to the invention can comply with the LiDAR sensor shown in figure 1,
15 for example, with the aim of the method according to the invention being to determine the components W_x , W_y and W_z of the wind speed on the x-, y- and z-axes, respectively.

By way of a non-limiting example, the method according to the invention works with a LiDAR sensor comprising any number of
20 beams.

The method according to the invention comprises the following steps:

- 25 1 - acquiring measurement signals;
- 2 - determining the mean wind direction and the mean wind speed;
- 3 - constructing a projection line;
- 4 - determining the time offset;
- 5 - determining the corrected measurement signal;
- 30 6 - determining the wind speed components.

These steps will be described throughout the remainder of the description. Steps 2 to 6 can be implemented using computing means, notably a computer. Steps 2 to 6 can be implemented
35 offline after step 1.

Figure 3 schematically illustrates, by way of a non-limiting example, the steps of the method according to one embodiment of

the invention. The measurement signals M_{acq} from the LiDAR sensor are initially acquired ACQ in at least one measurement plane. The measurement signals M_{acq} are subsequently used to determine CAR two wind characteristics for the measurement plane: the mean
5 wind direction Dir and the mean wind speed $\bar{v}$. The mean wind direction Dir is then used to construct the projection line DPR that can be defined by its angle Ψ . This angle Ψ and the mean wind speed $\bar{v}$ allow the time offset δt to be determined DTE between the measurement points and the projection line. The time
10 offset δt allows the corrected measurement signal M_{cor} to be determined COR that is implemented in a wind speed reconstruction REC so as to determine the wind speed components W_{est} in the measurement plane.

15 1 - Acquiring measurement signals

During this step, the measurement signals are acquired from the LiDAR sensor for at least one measurement plane. In other words, for each measurement point of at least one measurement plane,
20 the measurement signal originating from the LiDAR sensor is acquired. Advantageously, these measurement signals can be stored, notably in a computer memory, so as to be processed by computing means in the following steps.

25 In order to determine the wind speed components in several measurement planes, this step can be carried out for several measurement planes. In this case, the next steps can be carried out for each measurement plane.

30 Advantageously, the measurement signals can be acquired over a long time period, for example, over a duration that can vary from several days to a year or even more.

2 - Determining the mean wind direction and the mean wind speed

35 This step involves determining, for each considered measurement plane, the mean wind direction and the mean wind speed from the measurement signals acquired in step 1. For this step, a wind

reconstruction can be implemented that allows an approximation to be provided for the mean wind direction and the mean wind speed.

- 5 According to one embodiment of the invention, the wind can be reconstructed by way of a geometric reconstruction.

According to one aspect of the invention, for this wind reconstruction, a wind uniformity hypothesis can be used in the
10 considered measurement plane, so as to simplify this step.

Advantageously, the mean wind direction and the mean wind speed can be determined for a fixed duration or for a sliding time window, preferably the fixed duration or the sliding time window
15 ranges between 1 min and 1 h, and more preferably between 5 min and 30 min, and it can be 10 min, for example. Indeed, these time ranges allow characteristics representing the wind to be provided for implementing the next steps.

- 20 Advantageously, the mean wind speed can be determined in the considered measurement plane by means of a frozen turbulence hypothesis and by considering the vertical wind speed component to be zero.

- 25 According to one embodiment of the invention, the geometric reconstruction of the wind speed components can implement a "Moore-Penrose" pseudoinverse operation applied to the measurement signals. This geometric reconstruction at this stage allows an approximation to be provided of the wind speed
30 components, which differs from the determination of the wind speed components of step 6.

Figure 6 schematically illustrates, by way of a non-limiting example, a geometric parametrization of the measurement signals
35 of a LiDAR sensor (not shown). This figure shows four beams 2 of a LiDAR sensor. This figure also shows the x, y, z coordinate system from the centre O related to the LiDAR sensor. The centre O corresponds to the LiDAR sensor, the z-axis is the vertical

direction, and the x- and y-axes form a horizontal plane (defined in the same manner as for figure 1). Each beam 2 is oriented along a measurement axis represented by a vector Ob_i , with i varying from 1 to 4 to represent the 4 beams, and b_i representing the measurement points of the considered measurement plane. Each vector Ob_i is oriented relative to the x, y, z coordinate system by means of the angles θ_i and φ_i . The angle θ_i is defined in the (x, y) plane relative to the x-axis. The angle φ_i is defined relative to the z-axis.

By means of the geometric projections, the following equation can be written:

$$m_i(t) = (\sin(\varphi_i)\cos(\theta_i) \quad \sin(\varphi_i)\sin(\theta_i) \quad \cos(\varphi_i)) \begin{pmatrix} w_x(t) \\ w_y(t) \\ w_z(t) \end{pmatrix} = L_i w(t)$$

where $1, \dots, i, \dots, n$ are the measurement points of a measurement plane, $m_1, \dots, m_i, \dots, m_n$ are the measurement signals of the measurement plane, w_x, w_y, w_z are the wind speed components, L_i is a geometric reconstruction matrix dependent on angles θ_i and φ_i .

The "Moore-Penrose" pseudoinverse operation thus allows the estimated wind speed components in the measurement plane to be obtained by means of the measurement signals:

$$w(t) = \begin{pmatrix} w_x(t) \\ w_y(t) \\ w_z(t) \end{pmatrix} = L_1^{N+} \begin{pmatrix} m_1(t) \\ m_2(t) \\ \vdots \\ m_N(t) \end{pmatrix}$$

with:

$$L_1^N = \begin{pmatrix} \sin(\varphi_1)\cos(\theta_1) & \sin(\varphi_1)\sin(\theta_1) & \cos(\varphi_1) \\ \sin(\varphi_2)\cos(\theta_2) & \sin(\varphi_2)\sin(\theta_2) & \cos(\varphi_2) \\ \vdots & \vdots & \vdots \\ \sin(\varphi_N)\cos(\theta_N) & \sin(\varphi_N)\sin(\theta_N) & \cos(\varphi_N) \end{pmatrix}$$

and, for a matrix L , the exponent "+" means:

$$L^+ = L^T (LL^T)^{-1}$$

According to one implementation of the invention, this step can comprise a step of filtering the estimated speed, notably in order to limit any outlier values so as to make the method more reliable and robust.

According to one embodiment, this filtering can be implemented using a first-order low-pass filter so as to render a continuous and realistic representation of the measured wind state. It can be a variable-time constant filter. The older the last valid value that passed through the first-order filter, the more the time constant of the filter decreases (in other words, the weight of the state stored in the filter is increasingly low relative to the weight of the next valid value). This embodiment allows an instantaneous low-frequency, denoised and realistic value to be acquired of the wind state contained in the radial measurements.

Once the wind speed components have been approximated with this method, the mean wind direction in the considered measurement plane and the mean wind speed in the considered measurement plane are determined.

3 - Constructing a projection line

This step involves constructing a projection line perpendicular to the mean wind direction determined in the previous step in each considered measurement plane. Thus, a projection line is constructed that is orthogonal to the mean wind direction. The projection line is in the horizontal measurement plane.

According to one embodiment of the invention, a projection line can be constructed that passes through the barycentre of the measurement points. This embodiment allows a projection line to be provided with a fixed point over time (i.e., invariant over time).

Figure 4 schematically illustrates, by way of a non-limiting example, the construction of this projection line according to a first embodiment. Figure 4 is a view of a horizontal measurement plane defined by the x- and y-axes. Four measurement points (b1, b2, b3, b4) are shown in this measurement plane. The barycentre of these measurement points is the point O, which in this example corresponds to the centre of the x, y coordinate

system in which the LiDAR sensor (not shown) is located. This figure also illustrates the wind speed vector WS , as well as its direction, the axis x' . The projection line y' passing through the point O , perpendicular to the axis x' , is thus constructed.

5 The other elements of figure 4 are described in the remainder of the description.

As a variant, a projection line passing through a measurement point can be constructed. Preferably, a projection line passing through the measurement point with the most recent measurement can be constructed. Indeed, with the measurement of a LiDAR sensor being carried out on a beam-by-beam basis, with a sampling rate, the measurements are not carried out at the same time for all the measurement points. Therefore, there is a point at which the measurement is more recent than for the other points. This variant allows a non-phase-shifted measurement to be provided, i.e., with a zero time offset (see the next steps). Taking into account the most recent measurement allows the accuracy of the method according to the invention to be increased.

20

Figure 5 schematically illustrates, by way of a non-limiting example, the construction of this projection line according to a second embodiment. Figure 5 is a view of a horizontal measurement plane defined by the x - and y -axes. Four measurement points (b_1 , b_2 , b_3 , b_4) are shown in this measurement plane. The barycentre of these measurement points is the point O , which in this example corresponds to the centre of the x , y coordinate system in which the LiDAR sensor (not shown) is located. This figure also shows the wind speed vector WS . In this figure, the measurement point b_1 is considered to be the point with the most recent measurement. An axis x' parallel to the wind speed WS and passing through the measurement point b_1 is initially constructed, and then the projection line y' , passing through the measurement point b_1 and perpendicular to the axis x' , is constructed. The other elements of figure 5 are described in the remainder of the description.

35

4 - Determining the time offset

This step involves determining, within each considered measurement plane, a time offset between each measurement point and the projection line constructed in the previous step, and
5 by means of said mean wind speed determined in step 2. The time offset is a duration that corresponds to the duration required for an air mass to travel the distance between the measurement point and the projection line, due to the wind. In brief, this step involves projecting each measurement point on the
10 projection line and determining the time offset between each measurement point and its projection on the projection line. It is an orthogonal projection in the measurement plane, and consequently the projection is obtained by the intersection of the projection line and a line parallel to the wind direction
15 passing through the measurement point. This step amounts to expressing the position of the measurement points on the projection line.

For the first embodiment of figure 4, the measurement points
20 (b1, b2, b3, b4) are initially projected on the projection line y'. The projected points (b1', b2', b3', b4') are thus obtained. The time required for the wind to travel each distance is subsequently determined: the distance between points b1 and b1', the distance between points b2 and b2', the distance between
25 points b3 and b3', and the distance between points b4 and b4'. These travel times correspond to the time offset.

For the second embodiment of figure 5, the measurement points
30 (b1, b2, b3, b4) are initially projected on the projection line y'. The projected points (b1', b2', b3', b4') are thus obtained. The time required for the wind to travel each distance is subsequently determined: the distance between points b2 and b2', the distance between points b3 and b3', and the distance between points b4 and b4'. These travel times correspond to the time
35 offset. Since measurement point b1 belongs to the projection line, point b1 is its own projection, and consequently the time offset for this point is zero.

According to one implementation of the invention, the time offset δt of the measurement point i can be determined with the formula:

$$\delta t_i = \frac{x_i \cos \Psi - y_i \sin \Psi}{\bar{v}}$$

5 where x_i and y_i are the coordinates of the measurement point i in the coordinate system associated with the considered measurement plane, $\bar{v}$ is the mean wind speed determined in step 2, and Ψ is the angle formed between the y -axis of the measurement plane and the projection line (which also
10 corresponds to the angle formed between the direction of the wind speed vector WS relative to the axis). This angle Ψ is illustrated in figures 4 and 5.

Preferably, the time offset is positive for the measurement
15 points located upstream of the projection line, and the time offset is negative for the measurement points located downstream of the projection line, with upstream and downstream being defined according to the mean wind direction.

20 5 - Determining the corrected measurement signal

This step involves determining, in each considered measurement plane and for each measurement point, a corrected measurement signal, with the corrected measurement signal corresponding to
25 the measurement signal at a considered time reduced by a duration corresponding to said time offset determined in the previous step (by way of a reminder, the time offset can be negative or positive). In other words, the measurements that would be carried out at the measurement points projected on the
30 projection line are determined. To this end, the actual measurements at the measurement points and the time offsets determined in the previous step are taken into account.

The corrected measurement then can be written as follows:

$$m'_i(t) = m_i(t - \delta t_i)$$

35 with i being the measurement points, m_i being the measurements acquired at the measurement point i , m'_i being the corrected measurement at the measurement point i , and δt_i being the time offset of the measurement point i . Given that the time offset

can be negative or positive, the time $t - \delta t_i$ can be less than the time t (i.e., prior to the time t) or greater than the time t (i.e., after the time t). Indeed, this formula is notably permitted by Taylor's frozen turbulence hypothesis, according to which the advection contributed by turbulent circulations themselves is small and, therefore, the advection of a field of turbulence past a fixed point can be taken to be entirely due to the mean flow. In other words, the entire air mass, including any turbulence, moves at the mean speed of the wind field.

According to one embodiment of the invention, when, at the time $t - \delta t$, no acquired actual measurement is available, an interpolation of the measurements before and after the considered measurement point then can be implemented in order to estimate the corrected measurement. Any interpolation method can be implemented, using, for example, a mean, a weighted mean, etc.

6 - Determining the wind speed components

This step involves determining, in each considered measurement plane, the wind speed components by means of the corrected measurement signals determined in the previous step. Determining the wind speed components from corrected measurements allows the size of the wind field homogeneity hypothesis to be reduced from two dimensions to one dimension (that of the projection line) by taking into account the temporal coherence of the LiDAR sensor measurements.

Indeed, for example, for a LiDAR sensor with four beams as illustrated in figures 1 and 2, for a measurement plane located 150 m away from the LiDAR sensor, and for a 28° aperture of the measurement beams, the surface area of the square delimited by the measurement points is $12,700 \text{ m}^2$, while the size of the projection line segment that is obtained with the method according to the invention (the line segment connecting all the projections of the measurement points), when the wind direction forms an angle of 45° relative to the x-axis, is 160 m.

According to one embodiment, a wind reconstruction method can be implemented.

- 5 Advantageously, the wind speed components can be determined by way of the following equation:

$$\begin{pmatrix} w_x(t) \\ w_y(t) \\ w_z(t) \end{pmatrix} = L_1^{N+} \begin{pmatrix} m_1(t - \delta t_1) \\ m_2(t - \delta t_2) \\ \vdots \\ m_N(t - \delta t_N) \end{pmatrix}$$

where w_x , w_y , w_z are the wind speed components, m_1 , m_2 , ..., m_N are the measurement signals from the measurement points 1 to N, δt is the time offset of the measurement points 1 to N, and L_1^{N+} is a matrix for geometrically reconstructing the wind speed components.

According to a preferred embodiment, the matrix for geometrically reconstructing the wind speed components can be identical to the one used in the embodiment of step 2. Thus, the following can be written:

$$L_1^N = \begin{pmatrix} \sin(\varphi_1)\cos(\theta_1) & \sin(\varphi_1)\sin(\theta_1) & \cos(\varphi_1) \\ \sin(\varphi_2)\cos(\theta_2) & \sin(\varphi_2)\sin(\theta_2) & \cos(\varphi_2) \\ \vdots & \vdots & \vdots \\ \sin(\varphi_N)\cos(\theta_N) & \sin(\varphi_N)\sin(\theta_N) & \cos(\varphi_N) \end{pmatrix}$$

and, for a matrix L, the exponent "+" means:

$$L^+ = L^T(LL^T)^{-1}$$

Furthermore, the present invention relates to a method for installing a wind turbine, wherein the following steps are implemented:

- 25 - determining the wind speed components by means of the method according to any one of the variants or combinations of variants described above, on at least one site (location);
- installing a wind turbine on the site according to the wind speed components.

30

During the installation step, the installed wind turbine can be determined in terms of dimensions, class, its structure, it is also possible to determine its orientation, and the control thereof according to the wind speed components.

According to one implementation of the invention, the first step can be repeated over several sites. The site most suitable for the installation of a wind turbine is subsequently determined according to the wind speed components. It notably can be the site where the wind speed is within an operating range that is suitable for energy recovery using a wind turbine.

Comparative example

The features and advantages of the method according to the invention will become apparent from reading the following example of an application.

The example relates to CFD (Computational Fluid Dynamics) simulation of the measurement signals of a ground-based and vertically oriented LiDAR sensor with nine beams. For this simulation, 600 s wind measurement signals are generated. Once the wind measurement signals are generated, the LiDAR sensor is modelled with beam projection in order to obtain radial measurements. In order to observe the phasing of the time signals, the lateral and vertical wind speed components are neutralised.

Figure 7 schematically illustrates, by way of a non-limiting example, a measurement plane of a LiDAR sensor with nine beams, with the measurement plane being located 130 m from ground level. This figure shows the position of the measurement points, numbered from 1 to 9, the orientation of the wind W , in this case determined over 600 s (for this example, the wind direction W is parallel to the x-axis), the projection line y' on which the measurements are projected (for this example, the projection line y' is parallel to the y-axis). Two values are indicated for each measurement point: the distance to the projection line in m and the time offset in s.

Figure 8 shows curves of the radial wind speed RWS in m/s as a function of time T in s, for measurement points 5 and 7, which

are the measurement points furthest away from the projection line. The upper figure shows the radial wind speed taking into account the directly acquired measurement signal, according to a method of the prior art AA for measurement points 5 and 7.

5 Since these points are spaced apart by 230 m, the measurements for these two points are not identical, and some variations of point 7 result from a time offset of the measurement variations of point 5, but all the variations observed at measurement point 7 cannot be directly deduced from the variations observed at
10 measurement point 5. Consequently, if the method of the prior art is applied directly, a temporal incoherence is present, which implies a lack of accuracy in determining the wind speed components. The lower figure shows the radial wind speed taking into account the corrected measurement signal, according to the
15 method of the invention, for measurement points 5 and 7. It should be noted that the method according to the invention allows good time synchronisation of the measurement signals: the curves are almost superposed. Thus, by virtue of this synchronisation, determining the wind speed components can be more accurate and
20 more reliable.

Patentkrav

1. Fremgangsmåde til bestemmelse af vindhastighedens komponenter ved hjælp af en LiDAR-sensor (1), hvilken LiDAR-sensor (1) er orienteret i det væsentlige lodret for at udføre målingerne i mindst ét i det væsentlige vandret måleplan (PM), hvor hvert måleplan (PM) omfatter mindst to målepunkter (b1, b2, b3, b4), kendetegnet ved, at følgende trin udføres:
 - a) Der opnås (ACQ) målesignaler fra LiDAR-sensoren (1) for hvert målepunkt (b1, b2, b3, b4) i det mindst ene måleplan (PM).
 - b) Den gennemsnitlige vindretning (Dir) og den gennemsnitlige vindhastighed (v) bestemmes i det mindst ene måleplan (PM) ved hjælp af en rekonstruktion af vinden ud fra målesignalerne.
 - c) I det mindst ene måleplan konstrueres en projektionslinje, der er vinkelret på den bestemte vindretning (Dir).
 - d) Der bestemmes en tidsforskydning (δt) mellem hvert målepunkt (b1, b2, b3, b4) i det mindst ene måleplan (PM) og den konstruerede projektionslinje ved hjælp af den bestemte gennemsnitlige vindhastighed (v).
 - e) For hvert målepunkt (b1, b2, b3, b4) i det mindst ene måleplan (PM) bestemmes et korrigeret målesignal, hvilket korrigeret målesignal svarer til målesignalet på et tidspunkt forud for det betragtede tidspunkt minus et tidsrum, der svarer til tidsforskydningen (δt), og
 - f) Komponenterne af vindhastigheden i det mindst ene måleplan (PM) bestemmes ved hjælp af de korrigerede målesignaler.
2. Fremgangsmåde ifølge krav 1, hvorved projektionslinjen konstrueres ved hjælp af en linje, der er vinkelret på vindretningen (Dir), og som går gennem målepunkternes (b1, b2, b3, b4) tyngdepunkt i det mindst ene måleplan (PM), eller som går gennem et målepunkt (b1, b2, b3, b4) i det mindst ene måleplan (PM).
3. Fremgangsmåde ifølge krav 2, hvorved projektionslinjen konstrueres ved hjælp af en linje, der er vinkelret på vindretningen (Dir), og som går gennem målepunktet (b1, b2, b3, b4) i det mindst ene måleplan, som har den seneste måling.

4. Fremgangsmåde ifølge et af de foregående krav, hvorved vindrekonstruktionen tager højde for en antagelse om vindens ensartethed i det mindst ene måleplan.

5

5. Fremgangsmåde ifølge et af de foregående krav, hvorved tidsforskydningen δt for målepunktet i bestemmes ved hjælp af formlen:

$$\delta t_i = \frac{x_i \cos \Psi - y_i \sin \Psi}{\bar{v}}$$

10 hvor x_i og y_i er målepunktets koordinater i referencerammen i i det koordinatsystem, der er knyttet til det mindst ene måleplan, $\bar{v}$ den bestemte gennemsnitlige vindhastighed og Ψ den vinkel, der dannes mellem y -aksen af det mindst ene måleplan og projektionslinjen.

15 6. Fremgangsmåde ifølge et af de foregående krav, hvorved det korrigerede målesignal bestemmes ved interpolation af målesignalerne før og efter det betragtede målepunkt.

20 7. Fremgangsmåde ifølge et af de foregående krav, hvorved vindhastighedens komponenter bestemmes ved hjælp af ligningen:

$$\begin{pmatrix} w_x(t) \\ w_y(t) \\ w_z(t) \end{pmatrix} = L_1^{N+} \begin{pmatrix} m_1(t - \delta t_1) \\ m_2(t - \delta t_2) \\ \vdots \\ m_N(t - \delta t_N) \end{pmatrix}$$

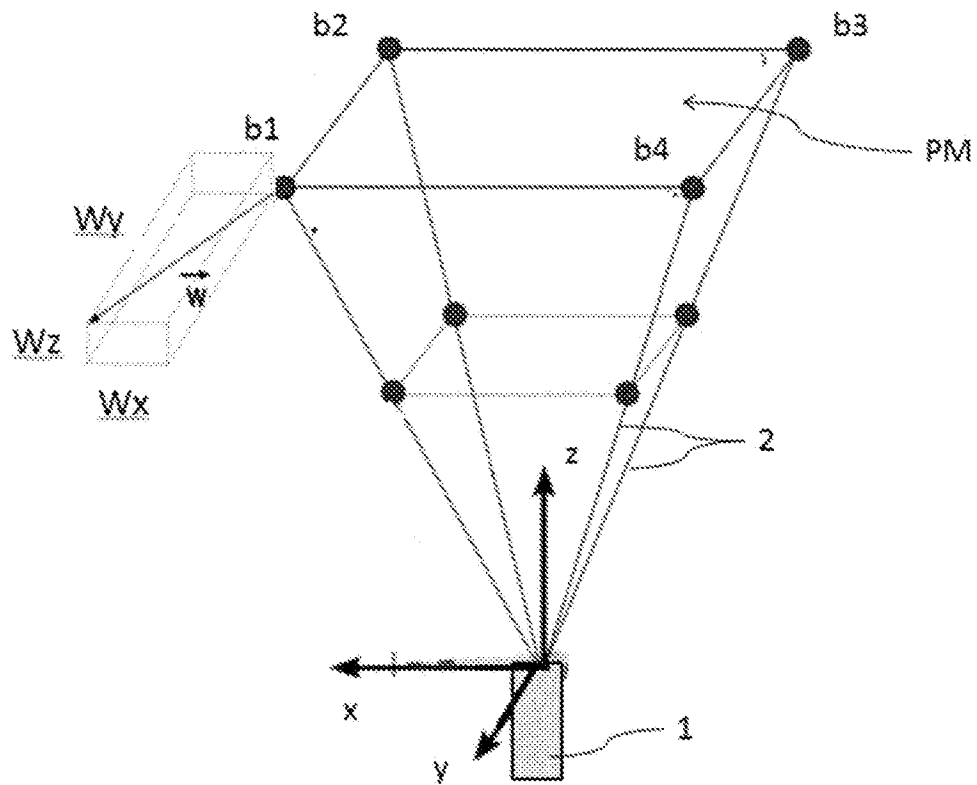
25 hvor w_x , w_y , w_z er vindhastighedens komponenter, m_1 , m_2 , ..., m_N målesignalerne fra målepunkterne 1 til N , δt tidsforskydningen for målepunkterne 1 til N , og L_1^{N+} en geometrisk rekonstruktionsmatrix af vindhastighedens komponenter.

8. Fremgangsmåde ifølge et af de foregående krav, hvorved den gennemsnitlige vindretning (Dir) og den gennemsnitlige vindhastighed (v) bestemmes for et fast tidsrum eller for et
30 glidende tidsvindue, idet det faste tidsrum eller det glidende tidsvindue fortrinsvis er på mellem 1 min og 1 time og fortrinsvis mellem 5 min og 30 min.

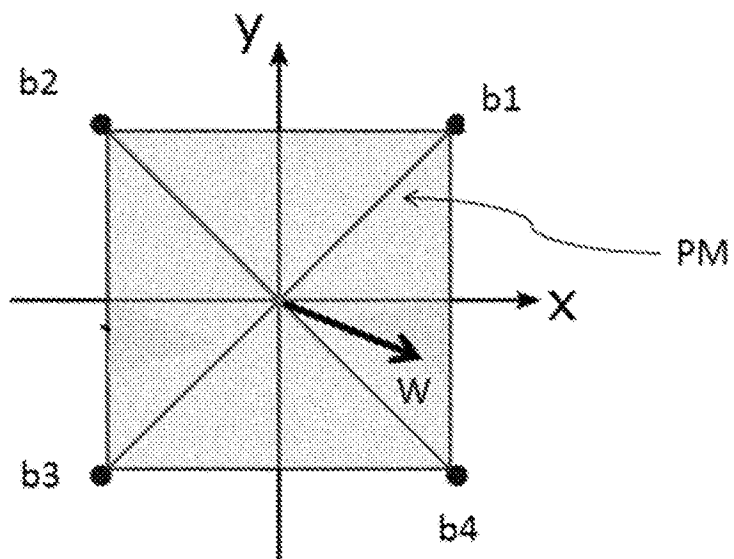
35 9. Fremgangsmåde ifølge et af de foregående krav, hvorved den gennemsnitlige vindhastighed (v) bestemmes i det mindst ene

måleplan ved hjælp af en antagelse om fast turbulens og ved at betragte vindhastighedens lodrette komponent som værende nul.

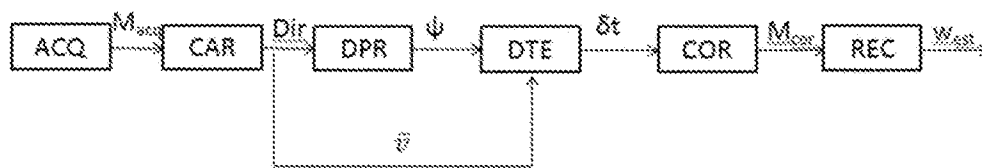
[Fig 1]



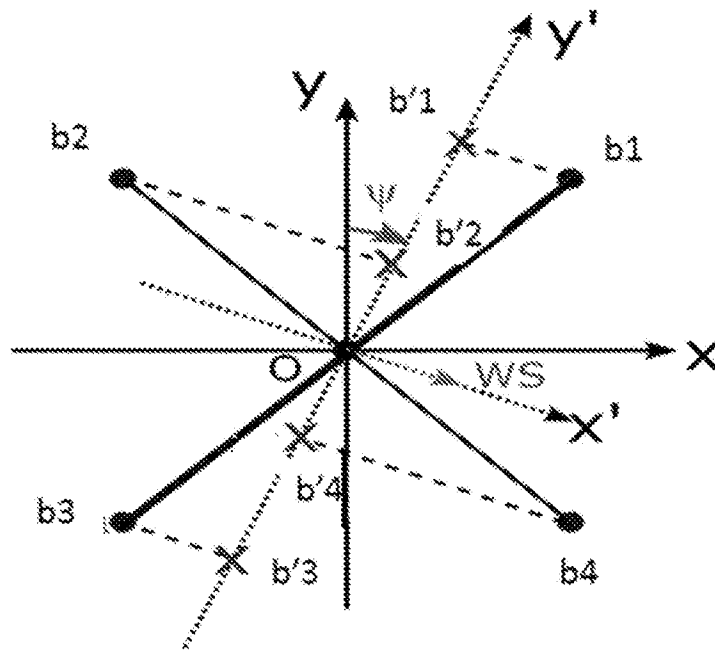
[Fig 2]



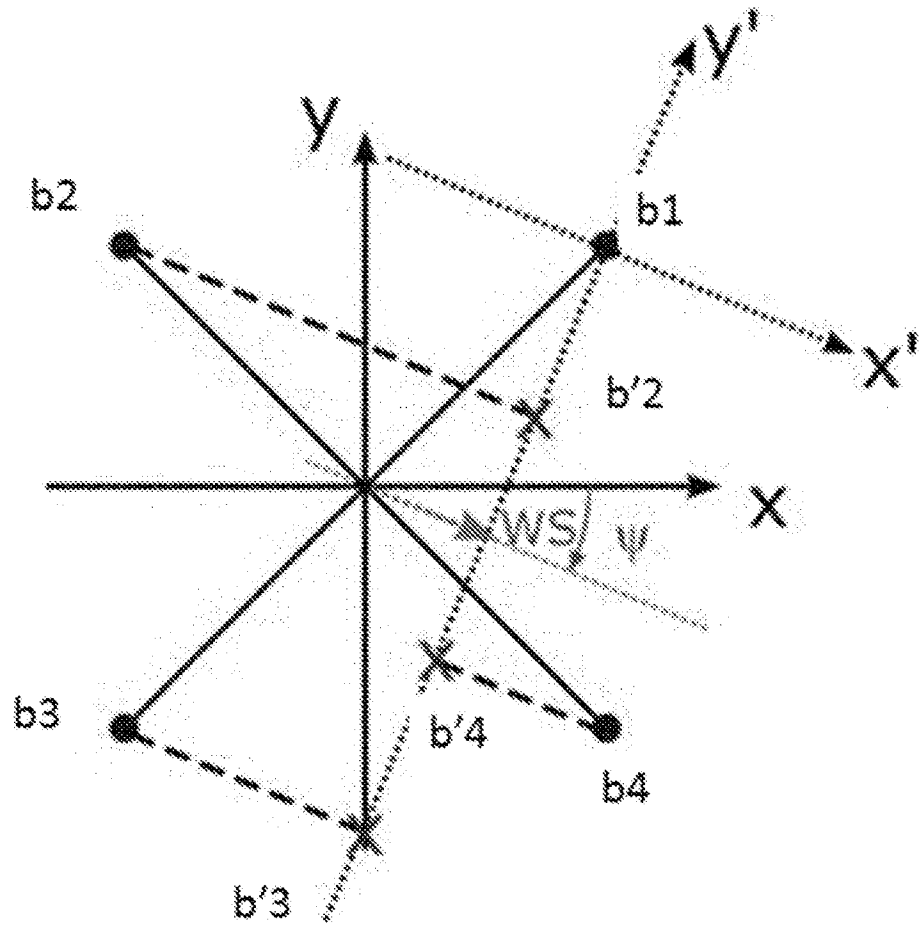
[Fig 3]



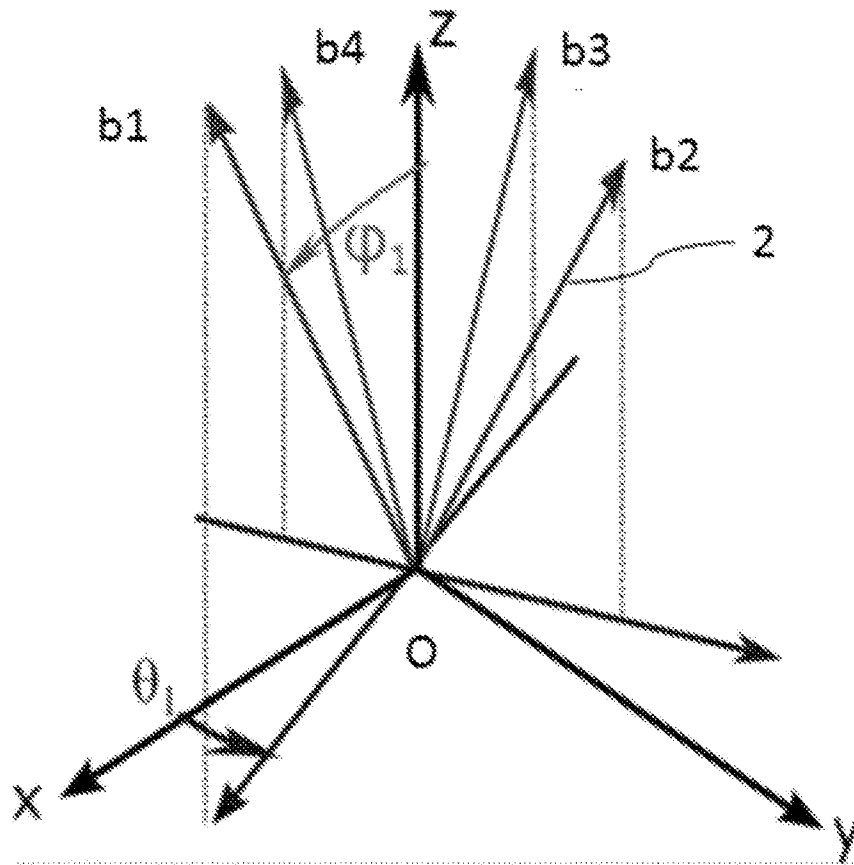
[Fig 4]



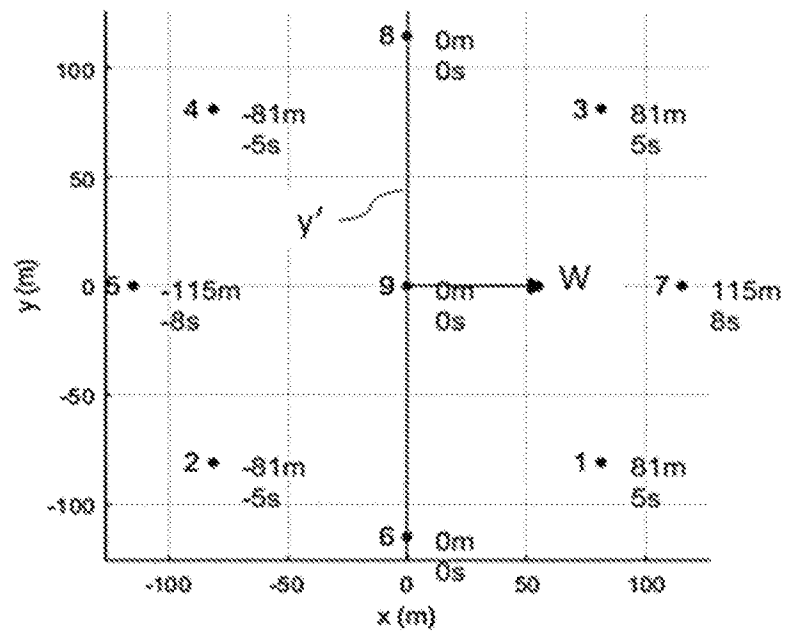
[Fig 5]



[Fig 6]



[Fig 7]



[Fig 8]

