(19) **DANMARK**

(10) **DK/EP 3754341 T3**

Patent- og
Varemærkestyrelsen

(12) Oversættelse af
europæisk patentskrift

---

(51) Int.Cl.: ***G 01 P 5/26 (2006.01)*** ***G 01 P 21/02 (2006.01)*** *F 03 D 7/02 (2006.01)*
G 01 S 7/497 (2006.01) *G 01 S 17/00 (2020.01)*

(45) Oversættelsen bekendtgjort den: **2022-11-07**

(80) Dato for Den Europæiske Patentmyndigheds
bekendtgørelse om meddelelse af patentet: **2022-08-10**

(86) Europæisk ansøgning nr.: **20178434.5**

(86) Europæisk indleveringsdag: **2020-06-05**

(87) Den europæiske ansøgnings publiceringsdag: **2020-12-23**

(30) Prioritet: **2019-06-19 FR 1906569**

(84) Designerede stater: **AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR**

(73) Patenthaver: **IFP Energies nouvelles, 1 & 4, Avenue de Bois-Préau, 92852 Rueil-Malmaison Cedex, Frankrig**

(72) Opfinder: **NGUYEN, Hoai-Nam, 1 et 4 avenue de Bois Préau, 92852 RUEIL-MALMAISON CEDEX, Frankrig**
GUILLEMIN, Fabrice, 1 et 4 avenue de Bois Préau, 92852 RUEIL-MALMAISON CEDEX, Frankrig

(74) Fuldmægtig i Danmark: **RWS Group, Europa House, Chiltern Park, Chiltern Hill, Chalfont St Peter, Bucks SL9 9FG, Storbritannien**

(54) Benævnelse: **FREMGANGSMÅDE TIL BESTEMMELSE AF DEN LODRETTE VINDHASTIGHEDSPROFIL OPSTRØMS FOR EN VINDMØLLE UDSTYRET MED EN FJERNDETEKTERINGSSENSOR MED LASER**

(56) Fremdragne publikationer:
WO-A1-2018/234409
CHO A ET AL: "Wind Estimation and Airspeed Calibration Using the UAV with a Single-Antenna GNSS Receiver and Airspeed Sensor", GNSS 2006 - PROCEEDINGS OF THE 19TH INTERNATIONAL TECHNICAL MEETING OF THE SATELLITE DIVISION OF THE INSTITUTE OF NAVIGATION (ION GNSS 2006), THE INSTITUTE OF NAVIGATION, 8551 RIXLEW LANE SUITE 360 MANASSAS, VA 20109, USA, 29 septembre 2006 (2006-09-29), pages 3050-3058, XP056009959,
P. TOWERS ET AL: "Real-time wind field reconstruction from LiDAR measurements using a dynamic wind model and state estimation : LiDAR wind field estimation", WIND ENERGY, vol. 19, no. 1, 21 novembre 2014 (2014-11-21), pages 133-150, XP055451329, GB ISSN: 1095-4244, DOI: 10.1002/we.1824

Description

Technical field

The present invention relates to the field of renewable energy and more particularly relates to the measurement of the 'fuel' of wind turbines, i.e. wind, with the objectives of wind prediction and of control (orientation, regulation of torque and speed) and/or diagnosis and/or surveillance of the wind turbine.

A wind turbine allows the kinetic energy of wind to be converted into electrical or mechanical energy. To convert wind into electrical energy, a wind turbine comprises the following elements:

- a tower allowing a rotor to be positioned high enough to allow it to rotate (necessary for horizontal-axis wind turbines) and/or this rotor to be positioned at a height that allows it to be driven by wind that is stronger and more regular than at ground level. The tower generally houses some of the required electric and electronic components (modulator, control, multiplier, generator, etc.);
- mounted at the top of the tower, a nacelle that houses mechanical, pneumatic and certain electric and electronic components necessary to operate the machine. The nacelle may turn so as to orient the machine in the right direction;
- fastened to the nacelle, a rotor comprising a plurality of blades (generally three) and the nose cone of the wind turbine. The rotor is driven by the energy of the wind, and it is connected by a mechanical shaft, directly or indirectly (via a gearbox and mechanical-shaft system), to an electric machine (electric generator, etc.) that converts the harvested energy into electrical energy. The rotor is potentially provided with control systems such as a system for controlling variable-angle blades or a system for controlling aerodynamic brakes;
- a transmission, made up of two shafts (mechanical shaft of the rotor and mechanical shaft of the electric machine) that are connected by a transmission (gearbox).

Since the beginning of the 1990s, there has been renewed interest in wind power, in particular in the European Union where the annual growth rate is about 20%. This growth is attributed to the inherent potential of wind power to generate electricity without carbon emissions. In order to sustain this growth, the efficiency of wind turbines must be further improved. To succeed in increasing the amount of electricity generated by wind power, effective generation tools and advanced control tools need to be developed to improve machine performance. Wind turbines are designed to generate electricity at the lowest possible cost. They are therefore generally built to reach their peak performance at a wind speed of about 15 m/s. It is unnecessary to design wind turbines to be at their most efficient at higher wind speeds, as these are uncommon. In case of wind speeds above 15 m/s, it is necessary to lose some of the additional energy contained in the wind in order to avoid any damage to the wind turbine. All wind turbines therefore incorporate a system for achieving power regulation into their design.

In the context of this power regulation, controllers have been designed for variable-speed wind-turbine generators. The objectives of these controllers are to maximize the generated electric power, to minimize fluctuations in the speed of the rotor, and to minimize fatigue of and application of extreme moments to the structure (blades, tower and platform).

Prior art

To optimize control, it is important to know the speed of the wind at the rotor of the wind turbine. Various techniques have been developed to that end.

In a first technique, an anemometer is used to estimate a wind speed at one point, but this imprecise technology does not allow an entire wind field to be measured or the three-dimensional components of the wind speed to be determined or indeed the vertical profile of the wind speed to be determined.

In a second technique, a lidar sensor (lidar being the acronym of light detection and ranging) may be used (the expressions "lidar" and "laser remote detection" are used interchangeably in this text). Lidar is an optical remote-sensing or measurement technology based on analysis of the properties of a beam returned to its emitter. This method in particular uses a pulsed laser to determine the distance to an object. Lidar sensors use visible or infrared light instead of the radio waves used by radars, which are based on a similar principle. The distance to an object or surface is determined by measuring the delay between the pulse and the detection of the reflected signal.

In the field of wind turbines, lidar sensors are predicted to be essential to correct operation of large wind turbines, especially now that their size and power are increasing (today 5 MW, soon 12 MW offshore). This type of sensor allows wind to be measured at distance, allowing initial calibration of wind turbines with a view to enabling them to deliver maximum power (power curve optimization). In this calibration step, the sensor may be positioned on the ground and oriented vertically (profiling), this allowing wind speed and direction and the altitude gradient of the wind to be measured. This application is especially critical since it allows energy-generating potential to be determined. This is important in the context of planning wind farms since the financial viability of the farm will depend thereon. However, this method might be considered costly since it requires a vertically oriented lidar sensor to be fixedly arranged on the ground or sea, in addition to the lidar sensor provided in the wind turbine for the application described below.

A second application involves placing a sensor of this type on the nacelle of the wind turbine, with a view to measuring the wind field in front of the wind turbine, the sensor being oriented almost horizontally to do so. Measuring the wind field in front of the wind turbine should allow turbulence to be detected in advance before it reaches the wind turbine shortly afterwards. However, current wind-turbine control and monitoring techniques do not allow the speed of the wind at the rotor, i.e. in the plane of the rotor, to be precisely estimated based on a measurement taken by a lidar sensor. Such an application is in particular described in patent application FR-3-013,777 (US-2015-145,253).

Wind speed varies as a function of altitude: the wind is stronger at high altitude than at ground level. In various wind-turbine control applications it is useful to know the vertical profile of the speed of the wind, or in other words the gradient of the speed of the wind as a function of altitude. The document Rozenn Wagner, Ioannis Antoniou, Søren M. Pedersen, Michael S. Courtney, and Hans E. Jørgensen (2009) 'The Influence of the Wind Speed Profile on Wind Turbine Performance Measurements', Wind Energy, 12, 348-362, 10.1002/we.297, in particular describes the relationship between wind-speed profile and wind-turbine performance. To give examples, this vertical wind-speed profile may be used in wind-turbine energy evaluations or to control the pitch angle (angle of orientation) of the blades of the wind turbine.

Conventionally, the vertical wind-speed profile used by lidar-sensor manufacturers is obtained by means of methods based on batch processing that are applied off-line. These methods are therefore not suitable for estimating the vertical wind-speed profile in real time.

In addition, other methods for determining the vertical wind-speed profile use mathematical representations thereof, the logarithmic profile and the power law being examples of such mathematical representations.

The logarithmic wind profile was created from a model of the turbulent boundary layer above a flat plate by Prandtl. It was subsequently found to be valid in unmodified form for strong winds in the atmospheric boundary layer near the surface of the ground or sea. Near such a surface, the logarithmic wind profile is then given by:

$$v_z = \frac{v_*}{\kappa} \ln \frac{z}{z_0} - \psi_m$$

where v_z is the longitudinal wind speed at the altitude z, v_* is the friction velocity, k=0.41 is the Von Karman constant, z_0 is the surface roughness and ψ_m is the diabatic correction of the vertical wind-speed profile. This logarithmic profile depends only on constants, is inaccurate at high altitude and is difficult to calibrate. In addition, this logarithmic profile is less accurate than the power law.

As for the power law, it is written as follows:

$$\frac{v_z}{v_{z0}} = \left(\frac{z}{z_0}\right)^{\alpha}$$

with v_z the longitudinal wind speed at the altitude z, z_0 is a reference altitude, v_{z0} is the longitudinal wind speed at the reference altitude z_0 and α the exponent of said power law.

This power law is generally used in wind-energy evaluations, where the speed of the wind at the height of a wind turbine must be estimated from observations of near-surface wind, or when data on the speed of the wind at various heights must be adjusted to a standard height. With respect to the logarithmic law, the power law is readily integrable over a height. This profile is widely used for engineering purposes because of its simplicity. Assuming neutral atmospheric conditions, it is well known that the power law produces more accurate wind-speed predictions than the logarithmic law, at altitudes ranging from 100 m to the upper part of the atmospheric boundary layer. For normal wind conditions on offshore sites (at sea), the exponent α is set at 1/7. However, when a constant exponent is used, it does not take account of the variation as a function of time and surface roughness. In addition, it does not take account of the displacement of winds from the surface due to the presence of obstacles, such as the wind turbine in the present case. Using a constant exponent may therefore result in rather erroneous estimates of the vertical profile of the speed of the wind.

Summary of the invention

The aim of the present invention is in particular to determine, in real time, an accurate vertical profile of the speed of the wind in a simple manner. With this aim, the invention relates to a method for determining the vertical profile of the speed of the wind upstream of a wind turbine, in which method measurements of wind speed are taken by means of a lidar sensor, then the exponent α of the power law is determined by means of an unscented Kalman filter and of the measurements, and this exponent α is then applied to the power law in order to determine the vertical profile of the speed of the wind.

The invention relates to a method for determining the vertical profile of the speed of the wind upstream of a wind turbine, said wind turbine being equipped with a lidar sensor directed upstream of said wind turbine, wherein the following steps are implemented:

a) the speed of the wind in at least one measurement plane upstream of said wind turbine is measured at at least two measurement points located at different altitudes by means of said lidar sensor;

b) a model of the vertical profile of the wind speed is constructed by means of a power law of the form:

$$\frac{v_z}{v_{z0}} = \left(\frac{z}{z_0}\right)^{\alpha}$$

with v_z the longitudinal wind speed at the altitude z, z_0 a reference altitude, v_{z0} the longitudinal wind speed at the reference altitude z_0 and α the exponent of said power law;

the method being characterized in that:

c) said exponent α of said power law is determined by means of an unscented Kalman filter by means of said measurements of the wind speed at said two measurement points; and

d) said vertical profile of the speed of the wind is determined by applying said determined exponent α to said model of the vertical profile of the wind speed.

According to one embodiment of the invention, said unscented Kalman filter is applied to a state model that comprises additive noise and multiplicative noise.

Advantageously, said state model is written as:

$$\begin{cases} x(k) & = x(k-1) + \eta(k-1), \\ y(k) & = \left(v_2(k) + \epsilon_2(k)\right)\left(\frac{z_1}{z_2}\right)^{x(k)} - \epsilon_1(k) \end{cases}$$

with $x(k) = \alpha(k)$ the state variable at the time k, $y(k) = v_1(k)$ the output of said state model corresponding to the longitudinal wind speed measured at the time k at measurement point 1, $\eta(k-1)$ is the variation in the exponent α at the time k-1, $v_2(k)$ the longitudinal wind speed measured at the time k at measurement point 2, z_1 the altitude of measurement point 1, z_2 the altitude of measurement point 2, $\epsilon_1(k)$ the noise in the speed v_1 at the time k, and $\epsilon_2(k)$ the noise in the speed v_2 at the time k.

Preferably, to apply said Kalman filter, the following augmented random variable x_a is considered:

$$x_a(k) = \begin{bmatrix} x(k) \\ \epsilon_2(k) \end{bmatrix}$$

with $x(k) = \alpha(k)$ the state variable at the time k, and $\epsilon_2(k)$ the noise in the speed v_2 at the time k. According to one aspect, said exponent α of said power law is determined by means of the following steps:

i) the state vector, the state of the covariance matrix and k are initialized to $\hat{x}_a(0|0) = m(0)$, $P(0|0) = P_0$, and k=0, respectively;

ii) at each time k, said measurements $v_1(k)$ and $v_2(k)$ of the wind speed are acquired at measurement points 1 and 2, with $y(k) = v_1(k)$; and

iii) at each time k, said exponent α of said power law is determined by means of the following equations:

$$\begin{cases} K(k) = P_{xy}P_{yy}^{-1} \\ x(k|k) = x(k|k-1) + K(k)\left(v_1(k) - m_y\right) \\ P(k|k) = P(k|k-1) - K(k)P_{yy}K(k)^T \end{cases}$$

with K the gain of the Kalman filter, P_{xy} the cross-covariance of the state and of the measurement, P_{yy} the predicted covariance of the measurement, m_y the predicted mean of the output, $v_1(k)$

the longitudinal wind speed measured at the time k at measurement point 1.

In addition, the invention relates to a method for controlling a wind turbine equipped with a lidar sensor, in which method the following steps are implemented:

a) said vertical profile of the speed of the wind upstream of the wind turbine is determined by means of the method according to one of the preceding features;

b) said wind turbine is controlled depending on said vertical profile of the speed of the wind upstream of said wind turbine.

The invention also relates to a computer program product that comprises code instructions arranged to implement the steps of a method according to one of the preceding features, when the program is executed on a processing unit of said lidar sensor.

Furthermore, the invention relates to a wind-turbine lidar sensor. Said sensor comprises a processing unit that implements a method according to one of the preceding features.

In addition, the invention relates to a wind turbine that comprises a lidar sensor according to one of the preceding features, said lidar sensor preferably being placed on the nacelle of said wind turbine or in the nose cone of the wind turbine.

Other features and advantages of the method according to the invention will become clear on reading the following description of non-limiting examples of embodiments, with reference to the appended drawings, which are described below.

List of figures

- Figure 1 illustrates a wind turbine equipped with a lidar sensor according to one embodiment of the invention,

- Figure 2 illustrates the steps of the method for determining the vertical wind-speed profile according to one embodiment of the invention,
- Figure 3 illustrates the steps of the method for controlling a wind turbine according to a second embodiment of the invention,
- Figure 4 is a curve of the measured radial wind speed at two altitudes, 200 m upstream of the wind turbine, as a function of time, for one example,
- Figure 5 is a curve of the estimated longitudinal speed at two altitudes, 200 m upstream of the wind turbine, as a function of time, for the example of Figure 4,
- Figure 6 is one example of a curve of the variation in the exponent α as a function of time for the example of Figure 4, and
- Figure 7 is a curve of the longitudinal speed estimated by means of the method according to one embodiment of the invention (based on the measurements of the example of Figure 4) and measured, 100 m upstream of the wind turbine, as a function of time.

Description of embodiments

The present invention relates to a method for determining the vertical profile of the speed of the wind upstream of a wind turbine (the notion "upstream" is defined with respect to the direction of the wind towards the wind turbine). The vertical profile of the speed of the wind or the vertical wind-speed profile (these two expressions being used interchangeably) here refers to the gradient of the speed of the wind as a function of altitude. The determined vertical wind-speed profile allows the vertical variation in the wind upstream of the wind turbine and in the plane of the rotor of the wind turbine to be determined. According to the invention, the wind turbine is equipped with a lidar sensor that is placed substantially horizontally with a view to measuring the speed of the wind upstream of the wind turbine.

According to the invention, the lidar sensor allows wind speed in at least one measurement plane upstream of the wind turbine to be measured. There are a number of different types of lidar sensor, for example scanning-lidar sensors, continuous-wave lidar sensors and pulsed-lidar sensors. Within the context of the invention, a pulsed lidar is preferably used. However, other lidar technologies may also be used while remaining within the scope of the invention.

The lidar sensor allows fast measurement. Therefore, using such a sensor enables fast, continuous and real-time determination of the vertical wind-speed profile. For example, the sampling rate of the lidar sensor may be comprised between 1 and 5 Hz (or even higher in the future), and it may be equal to 4 Hz. In addition, the lidar sensor allows information to be obtained on the wind upstream of the wind turbine, which information is related to the wind that will reach the wind turbine. The lidar sensor may therefore be used to determine the vertical wind-speed profile.

Figure 1 shows, schematically and non-limitingly, a horizontal-axis wind turbine 1 equipped with a lidar sensor 2 for the method according to one embodiment of the invention. The lidar sensor 2 is used to measure the speed of the wind at a given distance in a plurality of measurement planes PM (only two measurement planes have been shown). Knowing the wind measurement in advance *a priori* allows much information to be garnered. This figure also shows axes x, y and z. The reference point of this coordinate system is the centre of the rotor. Direction x is the longitudinal direction corresponding to the direction of the axis of the rotor, upstream of the wind turbine, this direction also corresponding to the measurement direction of the lidar sensor 2. Direction y, which is perpendicular to direction x, is the lateral direction located in a horizontal plane (directions x, y form a horizontal plane). Direction z is the vertical direction (substantially corresponding to the direction of the tower 4) directed upwards, axis z being perpendicular to axes x and y. The plane of the rotor has been indicated by the dash-dotted rectangle PR, it is defined by directions y, z for a zero value of x. The measurement planes PM are planes formed by the directions y, z at a distance from the rotor plane PR (for a non-zero value of x). The measurement planes PM are parallel to the rotor plane PR.

Conventionally, a wind turbine 1 allows the kinetic energy of the wind to be converted into electrical or mechanical energy. To convert wind into electrical energy, a wind turbine comprises the following elements:

- a tower 4 allowing a rotor (not shown) to be positioned high enough to allow it to rotate (necessary for horizontal-axis wind turbines) and/or this rotor to be positioned at a height that allows it to be driven by wind that is stronger and more regular than at ground level 6. The tower 4 generally houses some of the required electric and electronic components (modulator, control, multiplier, generator, etc.);
- mounted at the top of the tower 4, a nacelle 3 that houses mechanical, pneumatic and certain electric and electronic components (not shown) necessary to operate the machine. The nacelle 3 may turn so as to orient the machine in the right direction;
- fastened to the nacelle, the rotor comprising a plurality of blades 7 (generally three) and the nose cone of the wind turbine. The rotor is driven by the energy of the wind, and it is connected by a mechanical shaft, directly or indirectly (via a gearbox and mechanical-shaft system), to an electric machine (electric generator, etc.) (not shown) that converts the harvested energy into electrical energy. The rotor is potentially provided with control systems such as a system for controlling variable-angle blades or a system for controlling aerodynamic brakes;
- a transmission, made up of two shafts (mechanical shaft of the rotor and mechanical shaft of the electric machine) that are connected by a transmission (gearbox) (not shown).

As may be seen in Figure 1, which is an example of embodiment of a pulsed-lidar sensor, the lidar sensor 2 used has four measurement beams or axes (b1, b2, b3, b4). In a non-limiting manner, the method according to the invention would also work with a lidar sensor comprising any number of beams. The lidar sensor performs a point measurement at each measurement point (PT1, PT2, PT3, PT4), each measurement point being a point of intersection of one measurement plane PM and of one beam (b1, b2, b3, b4). These measurement points (PT1, PT2, PT3, PT4) have been represented by black circles in Figure 1. Processing the measurements measured at these measurement points (PT1, PT2, PT3, PT4) allows wind speed to be determined in the measurement planes PM and at a plurality of altitudes: the measurement points PT1 and PT2 are at an altitude higher than the altitude of the measurement points PT3 and PT4. The wind-modelling method described in French patent application FR-3,068,139 (WO-2018/234,409) may in particular be applied to do this.

Preferably, the lidar sensor 2 may be mounted on the nacelle 3 of the wind turbine 1 or in the nose cone of the wind turbine 1.

According to the invention, the method for determining the vertical profile of the speed of the wind upstream of the wind turbine comprises the following steps:
1) measuring the wind,
2) constructing a model of the vertical wind-speed profile
3) determining the exponent α
4) determining the vertical wind-speed profile.

These steps are carried out in real time. The step of constructing the model of the vertical wind-speed profile may be carried out beforehand and off-line.

Figure 2 illustrates, schematically and non-limitingly, the steps of the method for determining the vertical wind-speed profile according to one embodiment of the invention. The first step is a step of measuring (MES) the wind speed v1, v2 in at least one measurement plane at two different altitudes by means of the lidar sensor. A model (MOD) of the vertical wind-speed profile is constructed. The following step consists in determining the exponent α of the model (MOD) of the vertical wind-speed profile by means of an unscented Kalman filter (UKF) and of the wind speed measurements v1, v2. The determined exponent α is used with the model (MOD) of the vertical wind-speed profile to determine (PRO) the vertical wind-speed profile v(z).

<u>1) Measuring wind speed</u>

In this step, the wind speed is continuously measured in at least one measurement plane distant from the wind turbine, by means of the lidar sensor, at at least two measurement points located at different altitudes. Thus, the wind speed may be determined upstream of the wind turbine in at least one measurement plane at two different altitudes. The altitude of the measurement points is measured along the vertical axis (axis z in Figure 1) with respect to ground level or sea level. In this step, wind speed may for example be measured at measurement point PT1 ("upper" point) and at measurement point PT3 ("lower" point) of Figure 1.

According to one embodiment of implementation of the invention, the measurement planes may be distant by a longitudinal distance (along axis x in Figure 1) preferably comprised between 50 and 400 m from the rotor plane. It is thus possible to determine the variation in wind speed over a long distance upstream of the wind turbine, this also allowing the accuracy with which the vertical wind-speed profile is determined to be increased.

Alternatively, the measurement planes may be closer or further away than the preferred interval.

According to one non-limiting example of embodiment, the lidar sensor may take measurements in ten measurement planes, which may in particular be located at distances of 50, 70, 90, 100, 110, 120, 140, 160, 180 and 200 m from the rotor plane respectively.

According to one embodiment of the invention, wind speed measurements may be taken at a plurality of measurement points at each altitude. For example, the wind speed may be measured at the two measurement points PT1, PT2 ("upper" points) and at the two measurement points PT3, PT4 ("lower" points). In this case, the wind speed measured at one altitude may be a combination (the mean for example) of the wind speeds measured at this altitude.

In order to increase the accuracy of the following steps, wind speed may be measured in a plurality of measurement planes.

According to one implementation of the invention, the lidar sensor may allow radial speed (speed along the axis of the measurement beam of the lidar sensor) to be measured. In this case, the method may comprise a step of determining longitudinal speed (speed along the axis x of Figure 1) from the radial speed, by any known method, and in particular by projecting the radial speed onto the longitudinal axis, or by means of a wind-reconstruction method, for example the one described in patent application FR-3,068,139 (WO-2018/234,409).

2) Constructing the wind-speed model

In this step, a model of the vertical wind-speed profile is constructed by means of a power law (or any equivalent law) taking the form:

$$\frac{v_z}{v_{z0}} = \left(\frac{z}{z_0}\right)^{\alpha}$$

with v_z the longitudinal speed of the wind at the altitude z, z_0 a reference altitude, v_{z0} the longitudinal speed of the wind at the reference altitude z_0 and α the exponent of said power law.

The method according to the invention allows variations over time in the exponent α to be determined in order to make the wind-speed model accurate. One of the advantages of the power law is its simplicity. In addition, the power law generates more accurate wind-speed predictions than the logarithmic law, in particular at altitudes ranging from 100 m to within proximity to the upper part of the atmospheric boundary layer.

3) Determining the exponent α

In this step, the exponent α of the power law is determined by means of an unscented Kalman filter (UKF) and by means of the measurements of the speed of the wind at the measurement points. The unscented Kalman filter is a filtering algorithm that uses a system model to estimate the current hidden state of a system, then corrects the estimate using available sensor measurements. The UKF differs from the extended Kalman filter in that it uses the unscented transform to directly approximate the mean and covariance of the target distribution. The unscented Kalman filter may implement steps of state prediction and of measurement-based correction, these two steps being preceded by a prior step of computing "sigma points". These sigma points are a set of samples calculated so as to allow information on mean and variance to be accurately propagated through the space of a nonlinear function.

Thus, such a filter is well suited to rapidly determining the exponent α of the power law.

According to one embodiment of the invention, the unscented Kalman filter may be applied to a state model comprising additive noise and multiplicative noise. The additive and multiplicative noise comes from the measurements of wind speed at a plurality of altitudes. Additive noise is said to be additive because it appears as an added term in the state model. Multiplicative noise is said to be multiplicative because it appears as a term multiplying the input of the state model. This embodiment allows the exponent α of the power law to be accurately determined.

Advantageously, the state model may be written as:

$$\begin{cases} x(k) &= x(k-1) + \eta(k-1), \\ y(k) &= \left(v_2(k) + \epsilon_2(k)\right)\left(\frac{z_1}{z_2}\right)^{x(k)} - \epsilon_1(k) \end{cases}$$

with $x(k) = \alpha(k)$ the state variable at the time k, $y(k) = v_1(k)$ the output of the state model corresponding to the longitudinal speed of the wind measured at the time k at measurement point 1, $\eta(k-1)$ the variation in the exponent α at the time k-1, $v_2(k)$ the longitudinal speed of the wind measured at the time k at measurement point 2, z_1 the altitude of measurement point 1, z_2 the altitude of measurement point 2, $\epsilon_1(k)$ the noise in the speed v_1 at the time k, and $\epsilon_2(k)$ the noise in the speed v_2 at the time k. In this state model, $\epsilon_1(k)$ is additive noise and $\epsilon_2(k)$ is multiplicative noise.

In order to determine the exponent α by means of the unscented Kalman filter, the following augmented random variable x_a may be considered:

$$x_a(k) = \begin{bmatrix} x(k) \\ \epsilon_2(k) \end{bmatrix}$$

with $x(k) = \alpha(k)$ the state variable at the time k, and $\epsilon_2(k)$ the noise in the speed v_2 at the time k.

According to one implementation of the invention, the exponent α of the power law may be determined by means of the following steps:

i) the state vector, the state of the covariance matrix and k are initialized to $\hat{x}_a(0|0) = m(0)$, $P(0|0) = P_0$, and k=0, respectively;

ii) at each time k, said measurements $v_1(k)$ and $v_2(k)$ of the wind speed are acquired at measurement points 1 and 2, with $y(k) = v_1(k)$; and

iii) at each time k, said exponent α of said power law is determined by means of the following equations:

$$\begin{cases} K(k) = P_{xy}P_{yy}^{-1} \\ x(k|k) = x(k|k-1) + K(k)\big(v_1(k) - m_y\big) \\ P(k|k) = P(k|k-1) - K(k)P_{yy}K(k)^T \end{cases}$$

with K the gain of the Kalman filter, P_{xy} the cross-covariance of the state and of the measurement, P_{yy} the predicted covariance of the measurement, m_y the predicted mean of the output, $v_1(k)$ the longitudinal speed of the wind measured at the time k at measurement point 1.

According to one embodiment of the invention, the unscented Kalman filter may be implemented by means of the various steps described below.

The following notation is used:

- $x(k|k-1)$ is the estimate of $x(k)$ obtained based on the measurements of the time $k-1$;
- $x(k|k)$ is the estimate of $x(k)$ obtained based on the measurements of the time k;
- $P(k|k-1)$ is the error variance based on the measurements of the time k-1; and
- $P(k|k)$ is the error variance based on the measurements of the time k.

Q is the variance of the system noise $\eta(k)$.

Since the equation is linear, the prediction step may be written as:

$$\begin{aligned} x(k|k-1) &= x(k-1|k-1) \\ P(k|k-1) &= P(k-1|k-1) + Q \end{aligned}$$

Things are more complicated for the correction step due to the presence of both additive and multiplicative noise. To overcome this difficulty, the following augmented random variable may be considered:

$$x_a(k) = \begin{bmatrix} x(k) \\ \epsilon_2(k) \end{bmatrix}$$

After the prediction step, the distribution of the augmented random variable $x_a(k)$ may be given by a normal distribution denoted by N:

$$x_a(k|k-1) \sim N\left(m_{xa}, P_{xa}\right)$$

with:

$$m_{xa} = \begin{bmatrix} x(k|k-1) \\ 0 \end{bmatrix}, \; P_{xa} = \begin{bmatrix} P(k|k-1) & 0 \\ 0 & R_2(k) \end{bmatrix}$$

where $R_2(k)$ is the variance of the noise $\epsilon_2(k)$ in the speed v_2 at the time k.

The sigma points, denoted χ_0, χ_i, χ_{i+n}, associated with the mean m_{xa} and with the covariance matrix P_{xa} may be calculated in the following way:

$$\begin{cases} \chi_0 & = m_{xa} \\ \chi_i & = m_{xa} + \sqrt{n+\lambda} S_i, \; i = \overline{1,n} \\ \chi_{i+n} & = m_{xa} - \sqrt{n+\lambda} S_i, \; i = \overline{1,n} \end{cases}$$

where n=2, and S is a square root of P_{xa}, and

$$\lambda = \mu^2(n+\kappa) - n$$

with μ a scalar parameter determining the dispersion of the sigma points and κ a secondary resize parameter.

$\chi_{i,x}$ and $\chi_{i,\epsilon}$ may then be defined as the first and second components of χ_i. The sigma points are propagated through the measurement model in the following form, for any i comprised between 1 and 2n:

$$y_i(k) = (v_2(k) + \chi_{i,\epsilon}) \left(\frac{z_1}{z_2}\right)^{\chi_{i,x}}$$

The next step consists in calculating the predicted mean m_y, the predicted covariance of the measurement P_{yy} and the cross-covariance of the state and of the measurement P_{xy}.

$$\begin{cases} m_y = \sum_{i=0}^{2n} W_i^m y_i(k), \\ P_{yy} = \sum_{i=0}^{2n} W_i^c (y_i - m_y)(y_i - m_y)^T + R_1(k) \\ P_{xy} = \sum_{i=0}^{2n} W_i^c (\chi_{i,x} - x(k|k-1))(y_i - m_y)^T \end{cases}$$

where $R_1(k)$ is the variance of the noise $\epsilon_1(k)$ in the speed v_1 at the time k, W_i^m and W_i^c being weights defined by:

$$W_0^m = \frac{\lambda}{(\lambda+n)}$$

$$W_i^m = \frac{1}{2(\lambda+n)}$$

$$W_0^c = \frac{1}{(\lambda+n)} + 1 - \mu^2 + \xi$$

$$W_i^c = \frac{1}{2(\lambda+n)}$$

with ξ a parameter used to incorporate any prior knowledge of the distribution of the augmented random variable x_a.

The gain of the Kalman filter, the state estimation and the covariance matrix at the time k may then be expressed as:

$$\begin{cases} K(k) = P_{xy}P_{yy}^{-1} \\ x(k|k) = x(k|k-1) + K(k)(v_1(k) - m_y) \\ P(k|k) = P(k|k-1) - K(k)P_{yy}K(k)^T \end{cases}$$

Given that $x(k) = \alpha$, these equations allow the exponent α of the power law to be determined, this exponent being variable over time.

4) Determining the vertical wind-speed profile

In this step, the vertical profile of the speed of the wind upstream of the wind turbine is determined, using the model of the vertical wind-speed profile that was constructed in step 2) with the exponent α determined in step 3). Thus, the method according to the invention allows wind speed at any point in space upstream of the wind turbine to be determined.

Preferably, the method according to the invention allows the longitudinal wind speed at any point in space upstream of the wind turbine to be determined.

According to one embodiment of the invention, in the power law, the reference z_0 may be considered to be the altitude of any measurement point of the lidar sensor (which measurement point may be different from the measurement points used in step 1)), and the speed v_{z0} may be considered to be the wind speed measured at the measurement point in question. The vertical wind-speed profile may thus be determined in the measurement plane by applying the power law.

Alternatively, in the power law, any reference z_0 may be considered (a point in the rotor plane, for example) and the speed v_{z0} may be considered to be the estimated (reconstructed) wind speed at the point in question. It is thus possible to determine the wind speed in any plane in space, including the rotor plane. To reconstruct the wind speed, any wind-reconstruction method may be applied, in particular the one described in patent application FR-3,068,139 (WO-2018/234,409), the main steps of which will now be summarized:

- meshing the space located upstream of said lidar sensor, the mesh formed comprising estimation points and measurement points,
- measuring the amplitude and direction of the wind at the various measurement points,
- estimating the amplitude and direction of the wind at any given time for all of the estimation points by means of a recursive least-squares method to optimize a cost function (also referred to as the objective function), and
- reconstructing the incident wind field in three dimensions and in real time for all of the discretized points.

The present invention also relates to a method for controlling a wind turbine equipped with a lidar sensor. The following steps are carried out in this method:

– the vertical profile of the speed of the wind upstream of the wind turbine is determined by means of the method for determining the vertical wind-speed profile according to any one of the variants described above; and

– the wind turbine is controlled depending on the vertical profile of the speed of the wind upstream of said wind turbine.

Accurate real-time prediction of the vertical profile of the speed of the wind upstream of the wind turbine allows the wind turbine to be controlled correctly, in terms of minimization of effects on the structure of the wind turbine and of maximization of harvested energy. Specifically, by means of this control technique, the lidar allows the speed of the wind that will reach the wind turbine to be anticipated based on these predictions, and thus equipment of the wind turbine to be reconfigured in advance so that, when the estimated wind reaches the wind turbine, it is in an optimum configuration for this wind. The lidar sensor thus allows loads on the structure, the blades and tower of which represent 54% of the cost, to be decreased. Therefore, using a lidar sensor allows the structure of the wind turbine to be optimized, and therefore costs and maintenance to be decreased.

According to one implementation of the invention, the inclination angle of the blades and/or the generator torque of the wind-turbine generator may be controlled depending on wind speed. Preferably, the inclination angle of individual blades may be controlled. Other types of regulating device may also be used. Controlling blade inclination allows harvested energy to be optimized depending on the wind incident on the blades.

According to one embodiment of the invention, the inclination angle of the blades and/or the generator torque may be determined by means of wind-turbine maps depending on the wind speed at the rotor. For example, the control method described in patent application FR-2,976,630 A1 (US 2012-0,321,463) may be applied.

Figure 3 illustrates, schematically and non-limitingly, the steps of the method for controlling a wind turbine according to one embodiment of the invention. The first step is a step of measuring (MES) the wind speed v1, v2 in at least one measurement plane at two different altitudes by means of the lidar sensor. A model (MOD) of the vertical wind-speed profile is constructed. The following step consists in determining the exponent α of the model (MOD) of the vertical wind-speed profile by means of an unscented Kalman filter (UKF) and of the wind speed measurements v1, v2. The determined exponent α is used with the model (MOD) of the vertical wind-speed profile to determine (PRO) the vertical wind-speed profile $v(z)$. The vertical wind-speed profile $v(z)$ is then used to control (CON) the wind turbine.

In addition, the invention relates to a computer program product comprising code instructions arranged to implement the steps of one of the methods described above (method for determining the vertical wind-speed profile, or control method). The program is executed on a processing unit of the lidar sensor, or on any analogous means, connected to the lidar sensor or to the wind turbine.

According to one aspect, the present invention also relates to a lidar sensor for a wind turbine, which lidar sensor comprises a processing unit configured to implement one of the methods described above (method for determining the vertical wind-speed profile, or control method).

According to one implementation of the invention, the lidar sensor may be a scanning-lidar sensor, a continuous-wave lidar sensor or a pulsed-lidar sensor. Preferably, the lidar sensor is a pulsed-lidar sensor.

The invention also relates to a wind turbine, in particular an offshore (at sea) or an onshore (on land) wind turbine equipped with a lidar sensor such as described above. According to one embodiment of the invention, the lidar sensor may be placed on the nacelle of the wind turbine or in the nose cone of the wind turbine. The lidar sensor is directed so as to take a measurement of the wind upstream of the wind turbine (i.e. in front of the wind turbine and along the longitudinal axis thereof, which has been represented by the axis x in Figure 1). According to one embodiment, the wind turbine may be similar to the wind turbine illustrated in Figure 1.

As regards embodiment of the control method, the wind turbine may comprise control means, for example for controlling the inclination angle (or pitch angle) of at least one blade of the wind turbine or for controlling generator torque, in order to implement the method according to the invention.

Examples

Features and advantages of the method according to the invention will become clearly apparent upon reading the following example of application.

In this example, the wind speed estimated at a point upstream of the wind turbine, based on the vertical wind-speed profile determined using the method according to one embodiment of the invention is compared. To do this, for a distance of 200 m upstream of the wind turbine, wind speeds are measured at two measurement points located at different altitudes with a view to estimating, in real time, the exponent α of the power law, by means of the method according to one embodiment of the invention. Next, for a distance of 100 m upstream of the wind turbine, the vertical wind-speed profile determined with the exponent α is applied to determine the longitudinal wind speed at a predetermined altitude by means of a measurement of the longitudinal wind speed at a known altitude.

In this example, a 4-beam pulsed lidar that takes measurements in measurement planes located 100 m and 200 m from the wind turbine is considered.

Figure 4 shows radial wind speed RWS in m/s (i.e. in the direction of the measurement beam) measured for two measurement points (which may correspond to measurement points PT1 and PT3 of Figure 1) as a function of time T in 10^4 s for one day of measurement. This radial wind speed is measured in a measurement plane 200 m upstream of the wind turbine. The measured speed v1 in light grey corresponds to the speed measured at the lowermost measurement point. The measured speed v2 in dark grey corresponds to the speed measured at the uppermost measurement point. As expected, the speed measured at the uppermost measurement point is greater than the speed measured at the lowermost measurement point. In this figure, it will be noted that the lidar sensor does not take measurements all the time, due to a blade blocking effect.

Figure 5 is a curve of longitudinal wind speed wx in m/s (i.e. in direction x in Figure 1) as a function of time T in 10^4 s, corresponding to one day of measurement. The longitudinal wind speed wx is estimated from the radial wind speed RWS of Figure

4. This longitudinal speed is estimated in a measurement plane 200 m upstream of the wind turbine. The longitudinal speed wx1 in light grey corresponds to the longitudinal speed estimated at the lowermost measurement point. The longitudinal speed wx2 in dark grey corresponds to the longitudinal speed estimated at the uppermost measurement point.

The exponent α of the power law is determined from these speeds, by means of the method according to the invention. Figure 6 is a curve of the exponent α of the power law as a function of time T in 10^4 s. It may be seen that exponent α varies substantially – hence, the prior-art assumption under which a constant exponent α was considered is not realistic and does not allow the vertical profile of the speed of the wind to be accurately determined.

The lidar sensor also measures the wind speed in the measurement plane located 100 m upstream of the wind turbine, at two known altitudes. In order to demonstrate the accurate character of the method according to the invention, on the one hand the wind speed measured at the uppermost point at 100 m is taken as a reference, and on the other hand the wind speed at the uppermost measurement point at 100 m is estimated, by means of the method according to the invention, based on the speed of the wind at the lowermost measurement point at 100 m and on the exponent α determined in Figure 6 with the measurements of wind speed at 200 m. Figure 7 is a curve of the longitudinal wind speed wx in m/s (i.e. in direction x in Figure 1) at the uppermost measurement point as a function of time T in 10^4 s. This longitudinal speed is estimated in a measurement plane 100 m upstream of the wind turbine. Curve REF corresponds to the reference defined above and curve EST corresponds to the estimation by means of the method according to the invention such as defined above. It will be noted that the curves are very close, this demonstrating that the method according to the invention allows wind speed to be accurately determined.

Patentkrav

1. Fremgangsmåde til bestemmelse af den lodrette vindhastighedsprofil opstrøms for en vindmølle (1), hvor den lodrette vindhastighedsprofil er vindhastighedens gradient som funktion af højden, idet vindmøllen (1) er udstyret med en LIDAR-sensor (2), der er rettet opstrøms for vindmøllen (1), i hvilken fremgangsmåde de følgende trin udføres:

a) vindhastigheden måles (MES) i mindst ét måleplan (PM) opstrøms for vindmøllen i mindst to målepunkter (PT1, PT2, PT3, PT4), der befinder sig i forskellige højder, ved hjælp af LIDAR-sensoren (2)

b) en lodret profilmodel af vindhastigheden (MOD) konstrueres ved hjælp af en effektlov med formen:

$$\frac{v_z}{v_{z0}} = \left(\frac{z}{z_0}\right)^{\alpha}$$

hvor v_z er den langsgående vindhastighed i højden z, z_o er referencehøjden, v_{z0} er den langsgående vindhastighed i referencehøjden z_0, og α er eksponenten for effektloven, hvor den langsgående retning svarer til aksen af vindmøllens (1) rotor, idet fremgangsmåden er kendetegnet ved, at

c) eksponenten α for effektloven bestemmes ved hjælp af et unscented-Kalman-filter ved hjælp af målingerne af vindhastigheden i de to målepunkter (PT1, PT2, PT3, PT4), og

d) den lodrette vindhastighedsprofil (PRO) bestemmes ved at anvende den bestemte eksponent α på den lodrette vindhastighedsprofil.

2. Fremgangsmåde til bestemmelse af den lodrette vindhastighedsprofil ifølge krav 1, hvorved unscented-Kalman-filtret anvendes på en tilstandsmodel, der omfatter additiv støj og multiplikativ støj.

3. Fremgangsmåde til bestemmelse af den lodrette vindhastighedsprofil ifølge krav 2, hvorved tilstandsmodellen skrives som:

$$\begin{cases} x(k) & = x(k-1) + \eta(k-1), \\ y(k) & = (v_2(k) + \epsilon_2(k)) \left(\frac{z_1}{z_2}\right)^{x(k)} - \epsilon_1(k) \end{cases}$$

hvor x(k)=a(k) er tilstandsvariablen på tidspunktet k, y(k)=v1(k) er outputtet fra tilstandsmodellen svarende til den langsgående vindhastighed målt på tidspunktet k i målepunktet 1, η(k -1) er ændringen af eksponenten α på tidspunktet k-1, v2(k) er den langsgående vindhastighed målt på tidspunktet k i målepunktet 2, z1 er højden af målepunktet 1, z2 er højden af målepunktet 2, ε1(k) er støjen ved hastigheden v1 på tidspunktet k, og ε2(k) er støjen ved hastigheden v2 på tidspunktet k.

4. Fremgangsmåde til bestemmelse af den lodrette vindhastighedsprofil ifølge et af kravene 2 eller 3, hvorved den følgende udvidede stokastiske variabel x_a tages i betragtning til anvendelsen af Kalman-filtret:

$$x_a(k) = \begin{bmatrix} x(k) \\ \epsilon_2(k) \end{bmatrix}$$

hvor x(k)= α(k) er tilstandsvariablen på tidspunktet k, og ε2(k) er støjen ved hastigheden v2 på tidspunktet k.

5. Fremgangsmåde til bestemmelse af vindhastighedens lodrette profil ifølge et af de foregående krav, hvorved eksponenten α for effektloven bestemmes ved hjælp af følgende trin:

i) k=0, tilstandsvektoren $x\hat{}_{\alpha}$ $(0|0)$ = m(0) og kovariansmatricens tilstand, $P(0|0) = P_0$, initialiseres

ii) på hvert tidspunkt k foretages målingerne v1(k) og v2(k) af vindhastigheden i målepunkterne 1 og 2, med y(k)=v1(k), og

iii) på hvert tidspunkt k bestemmes eksponenten α for effektloven ved hjælp af følgende ligninger:

$$\begin{cases} K(k) = P_{xy} P_{yy}^{-1} \\ x(k|k) = x(k|k-1) + K(k)(v_1(k) - m_y) \\ P(k|k) = P(k|k-1) - K(k) P_{yy} K(k)^T \end{cases}$$

hvor K er forstærkningen af Kalman-filteret, Pxy er krydskovariansen af tilstanden og målingen, Pyy er den forudsagte kovarians af målingen, my er det forudsagte gennemsnit af outputtet, v1(k) er den langsgående vindhastighed målt på tidspunktet k i målepunktet 1, $P(k|k-1)$ er fejlvariansen fra målingerne af tiden k-1, og $P(k|k)$ er fejlvariansen fra målingerne af tiden k.

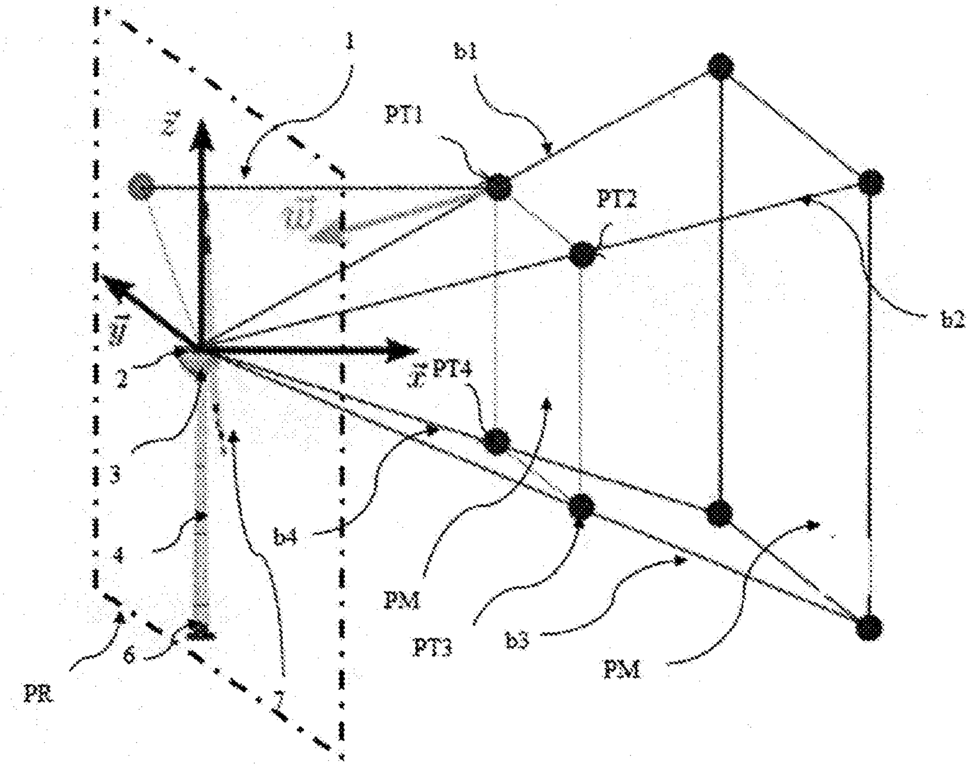
6. Fremgangsmåde til styring af en vindmølle (1), der er udstyret med en LIDAR-sensor (2), kendetegnet ved, at følgende trin udføres:
a) den lodrette vindhastighedsprofil opstrøms for vindmøllen (1) bestemmes ved hjælp af fremgangsmåden ifølge et af de foregående krav
b) vindmøllen (1) styres som funktion af den lodrette vindhastighedsprofil opstrøms for vindmøllen (1).

7. Computerprogramprodukt, kendetegnet ved, at det omfatter kodeinstruktioner, som er beregnet til at udføre trinnene i en fremgangsmåde ifølge et af de foregående krav, når programmet køres på en behandlingsenhed i LIDAR-sensoren (2).

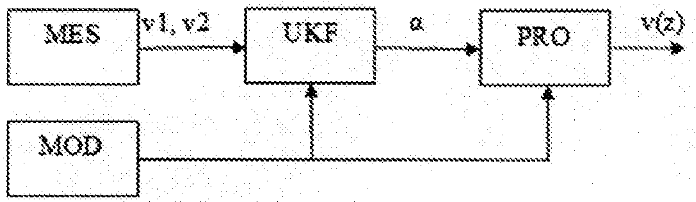
8. LIDAR-sensor (2) til en vindmølle, kendetegnet ved, at den omfatter en behandlingsenhed, der udfører en fremgangsmåde ifølge et af kravene 1 til 6.

9. Vindmølle (1), kendetegnet ved, at den omfatter en LIDAR-sensor (2) ifølge krav 8, hvilken LIDAR-sensor (2) fortrinsvis er placeret på vindmøllens (1) gondol eller i vindmøllens nav.

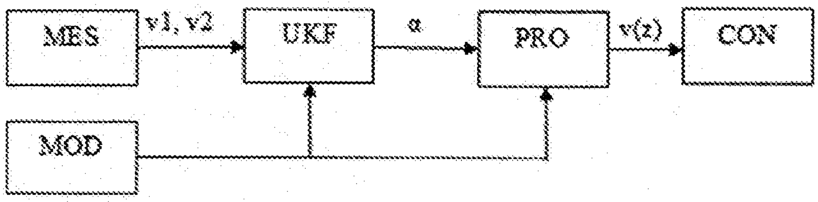
[Fig 1]



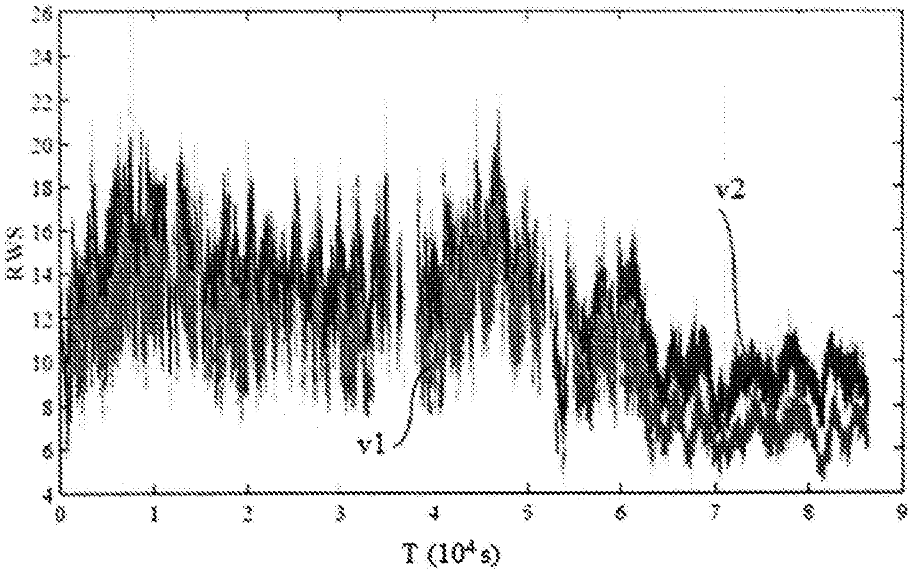
[Fig 2]



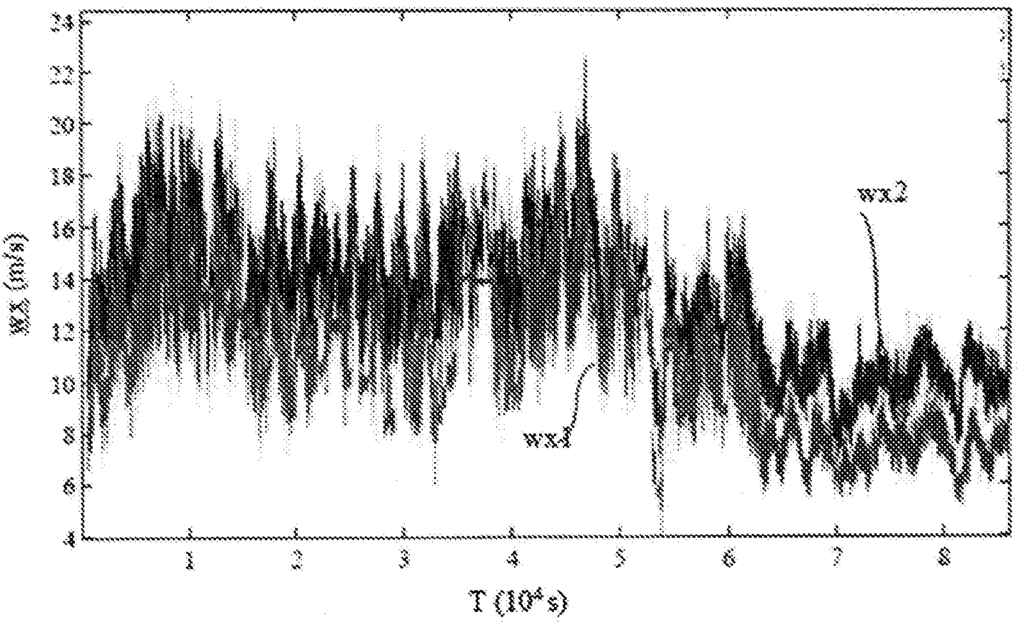
[Fig 3]



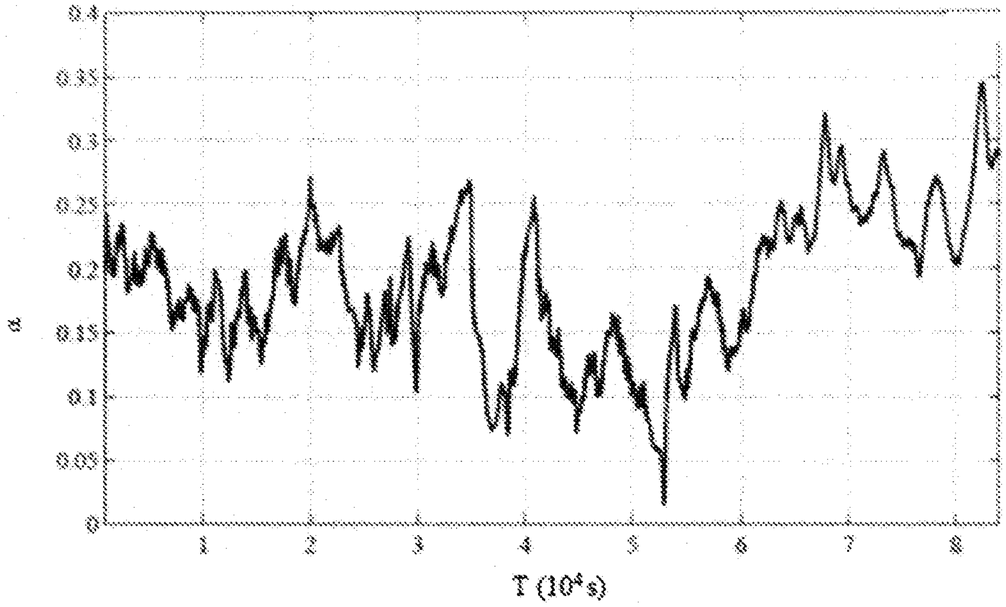
[Fig 4]


RWS
26
24
22
20
18
16
14
12
10
8
6
4
0
1
2
3
4
5
6
7
8
9
T (10⁴ s)
v1
v2

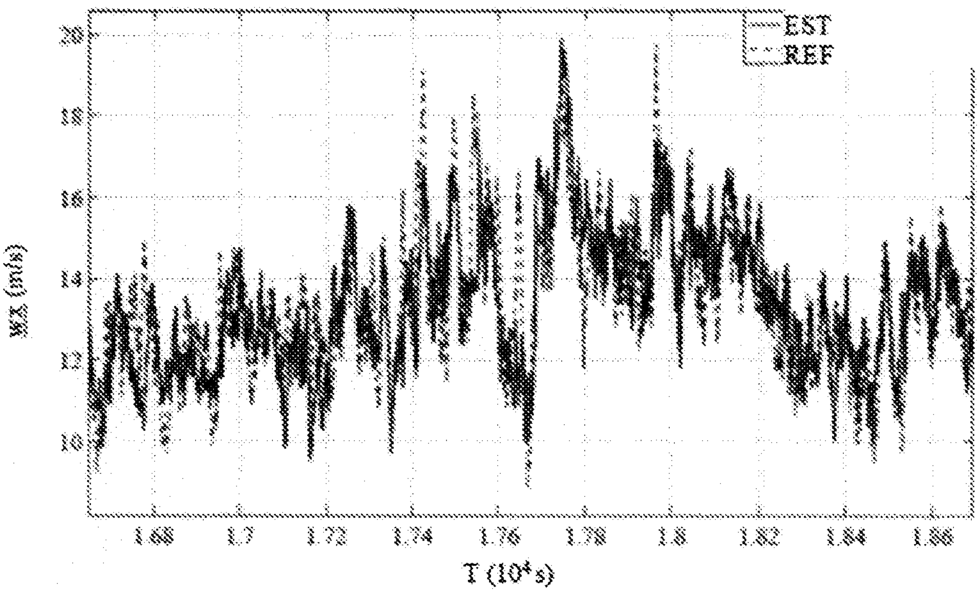
[Fig 5]


WX (m/s)
24
22
20
18
16
14
12
10
8
6
4
1
2
3
4
5
6
7
8
T (10⁴ s)
wx1
wx2

[Fig 6]


0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
α
1
2
3
4
5
6
7
8
T (10⁴ s)

[Fig 7]


EST
REF
20
18
16
14
12
10
WX (m/s)
1.68
1.7
1.72
1.74
1.76
1.78
1.8
1.82
1.84
1.86
T (10⁴ s)