(54) Title: DETERMINING A WIND TURBINE TOWER INCLINATION ANGLE

(57) Abstract: Determining a wind turbine tower inclination angle It is described a method of determining an inclination angle (Inc) of a wind turbine tower (103) at which a nacelle (105) is mounted, the method comprising: measuring plural acceleration values (Ay) of an acceleration of the nacelle (105) in a predetermined direction (113) relative to the nacelle for plural yawing positions (Nac_pos) of the nacelle (105); deriving the inclination angle based on the plural acceleration values.

FIG 1

DESCRIPTION

Determining a wind turbine tower inclination angle

5   Field of invention

The present invention relates to a method and to an arrange-
ment for determining an inclination angle of a wind turbine
tower and further relates to a method of monitoring a wind
10   turbine.

Art Background

The inclination of wind turbine towers may be required to
15   stay within some narrow tolerances to keep loads from gravity
at sufficiently low values, in particular to keep the loads
at a minimum. Over operation time of the wind turbine, the
inclination of the wind turbine tower may change due to
changes in the underground, in the basement or the settling
20   of the foundation.

Therefore, the inclination of the wind turbine tower may be
required to be measured and monitored to ensure that the
tower is installed correctly and stays in required inclina-
25   tion tolerances and also to ensure the integrity of the foun-
dation and to detect an unacceptable inclination.

Conventionally, the inclination of a wind turbine tower has
been measured manually by digital spirit levels or triangula-
30   tion. These methods are time-consuming, cumbersome and do not
provide sufficient accuracy in all circumstances.

Thus, there may be a need for a method and for an arrangement
of determining an inclination angle of a wind turbine tower,
35   which is reliable, simply to be performed and reliable and
further has sufficient accuracy.

Summary of the Invention

This need may be met by the subject matter according to the independent claims. Advantageous embodiments of the present
5   invention are described by the dependent claims.

According to an embodiment of the present invention it is provided a method of determining an inclination angle (in particular relative to a vertical direction) of a wind tur-
10   bine tower at which a nacelle is mounted, the method comprising measuring plural acceleration values of an acceleration of the nacelle in a predetermined direction relative to the nacelle for plural yawing positions of the nacelle and deriving the inclination angle based on the plural acceleration
15   values.

The inclination angle may be defined to be an angle of a longitudinal axis of the wind turbine tower and a vertical direction which points in the direction of the gravitational
20   force due to the earth gravity field. The wind turbine tower may be erected and installed at the surface of the earth or may be erected or installed offshore on a basement in the sea.

25   The nacelle may be mounted on top of the wind turbine tower and may have one or more accelerometers installed. The accelerometer(s) may be fixed relative to the nacelle. The predetermined direction (for example along which the accelerometer measures the acceleration) may for example be in the longitu-
30   dinal direction of the nacelle or in a direction orthogonal to the longitudinal direction of the nacelle or in a direction between the direction parallel to the longitudinal direction and the direction orthogonal to the longitudinal direction of the nacelle. For example, a conventionally avail-
35   able accelerometer may be employed to perform the measurements of the plural acceleration values.

Depending on the yawing position of the nacelle, the measured acceleration may change, in particular according to a trigonometric function. From the shape of a curve representing for example filtered acceleration values in dependence of the

5   yawing positions, the inclination angle may be derived. Thus, no additional equipment may be necessary to determine the inclination angle. Namely, an accelerometer may be conventionally installed in the nacelle of the wind turbine. Furthermore, a processor may be available which may be programmed to

10   perform the method of determining the inclination angle. Thus, the method is simple to implement, can be performed without interfering in the operation of the wind turbine and may have sufficient reliability and accuracy.

15   According to an embodiment of the present invention, the method further comprises measuring further plural acceleration values of an acceleration of the nacelle in a further predetermined direction relative to the nacelle for the plural yawing positions of the nacelle and deriving the inclina-

20   tion angle further based on the further plural acceleration values.

The further predetermined direction may for example be orthogonal to the predetermined direction. Conventionally, even

25   a 3D accelerometer may be available or installed in the nacelle. The 3D accelerometer may be capable of measuring accelerations in different directions. When using also the further plural acceleration value, the determination of the inclination angle may be more accurate and/or more reliable.

30   Thereby, the method may be improved.

According to an embodiment of the present invention, the method further comprises deriving an orientation/direction of the inclination of the wind turbine tower based on the plural

35   acceleration values.

The orientation or direction of the inclination may for example be characterized by a particular azimuthal angle, i.e. an

angle of a rotation around the yawing axis (or longitudinal direction of the wind turbine tower). The direction of the inclination may for example be detected by determining a phase angle in a trigonometric function fitted or adapted to
5   the plural acceleration values. When the orientation or direction of the inclination is determined, appropriate counter measures may be applied to avoid damage of components of the wind turbine.

10   According to an embodiment of the present invention, the deriving the inclination angle comprises averaging plural groups of the acceleration values associated with plural yawing position ranges to obtain for each yawing position range an associated averaged acceleration value and deriving the
15   inclination angle based on the averaged acceleration values.

This embodiment may also be referred to as a binning method. Each group of the plural groups may represent one bin of plural bins. Acceleration values in one bin may be averaged to
20   reduce noise and/or an influence of a possible oscillation of the wind turbine tower. The averaged acceleration values may be plotted against the yawing positions. The shape of this curve may contain information regarding the inclination angle as well as information regarding the orientation or direction
25   of the inclination angle. The average acceleration values may also represent filtered acceleration values. By filtering out noise and/or oscillations of the wind turbine tower, the method may further be improved.

30   According to an embodiment of the present invention, the deriving the inclination angle comprises deriving a mean acceleration value by averaging the plural acceleration values over all yawing positions, calculating plural acceleration differences between the averaged acceleration values and the
35   mean acceleration value, determining a maximum and a minimum of the acceleration differences, determining a difference between maximum and minimum and deriving an inverse of a trigo-

nometric function using a quantity proportional to the difference as an argument, to obtain the inclination angle.

These method steps may in particular be applied further to the binning method. By using these method steps, the amplitude of a periodic function, such as a trigonometric function, may be reliably calculated. The amplitude may represent a function of the inclination angle. Thereby, the inclination angle may reliably and in a simple manner be determined.

According to an embodiment of the present invention, the deriving the inclination angle comprises fitting a trigonometric function, in particular cosine or sine function, on the plural acceleration values, and deriving the inclination angle based on an amplitude of the trigonometric function.

For fitting the trigonometric function, the raw acceleration data or some kind of filtered acceleration data may be used. From theoretical considerations it is expected that the plural acceleration values, in particular when filtered, follow a sine function or a cosine function. Amplitude and phase of the sine or cosine function may relate to the magnitude of the inclination angle and the orientation or direction of the inclination angle. Thereby, the method can be easily performed.

According to an embodiment of the present invention, the different yawing positions cover samples of one or more circumferences, in particular at least 360°, of a rotation of the nacelle around an axis running along a longitudinal direction of the wind turbine tower.

When a full circumference is sampled, it may be ensured that the amplitude and the phase of the sine or cosine function may be reliably derived. However, if only a portion of a full circumference of acceleration values is available, at least an estimation of the inclination angle may be obtainable. In other embodiments, more than one round, such as two rounds,

three rounds, four rounds or even more rounds (in particular
n times 360°) of yawing positions may be run through while
the acceleration of the nacelle is measured and stored. Then,
an advantageous averaging may be performed to reduce noise
5 and scatter and to thus enable to derive the inclination an-
gle with even higher accuracy.

According to an embodiment of the present invention, the
method is performed during a cable untwist operation. A cable
10 untwist operation may conventionally be performed between two
times and ten times per month in order to untwist cables
which run from the wind turbine tower (which is fixed) to the
nacelle (which normally rotates to adjust the wind turbine
blades to face the wind direction which is constantly chang-
15 ing). Thus, no particular yawing actions (which are not per-
formed regularly during normal operation) of the nacelle are
necessary to perform the method. Thereby, interference of the
method with the normal operation of the wind turbine may fur-
ther be reduced.
20
According to an embodiment of the present invention, the na-
celle is continuously rotated around a yawing axis while the
accelerations are measured. In other embodiments, the nacelle
may be rotated in a stepwise manner around the yawing axis
25 and the acceleration may be measured at every step or after n
times a step.

According to an embodiment of the present invention, the pre-
determined direction (along which the acceleration is meas-
30 ured) is substantially parallel to a longitudinal direction
of the nacelle, the further predetermined direction is in
particular substantially orthogonal to a longitudinal direc-
tion of the nacelle. Thereby, a conventionally installed ac-
celerometer may be utilized for performing the method.
35 Thereby, costs may be reduced.

According to an embodiment of the present invention, the
measuring the plural acceleration values is performed using

an accelerometer installed at the nacelle. The accelerometer may be a conventionally available accelerometer.

According to an embodiment of the present invention it is
5   provided a method of monitoring a wind turbine, the method comprising performing a method according to one of the preceding embodiments, and raising an alarm, in particular shutting down the wind turbine, if the determined inclination angle exceeds a threshold.
10

It should be understood that features, individually or in any combination, disclosed, described, applied or employed for a method of determining an inclination angle of a wind turbine tower may also, individually or in any combination, applied
15   to, performed or provided for an arrangement for determining an inclination angle of a wind turbine tower according to embodiments of the present invention and vice versa.

According to an embodiment of the present invention it is
20   provided an arrangement for determining an inclination angle (e.g. relative to a vertical direction) of a wind turbine tower at which a nacelle is mounted, the arrangement comprising an accelerometer adapted to measure plural acceleration values of an acceleration of the nacelle in a predetermined
25   direction relative to the nacelle for plural yawing positions of the nacelle, and a processor adapted to derive the inclination angle based on the plural acceleration values.

It has to be noted that embodiments of the invention have
30   been described with reference to different subject matters. In particular, some embodiments have been described with reference to method type claims whereas other embodiments have been described with reference to apparatus type claims. However, a person skilled in the art will gather from the above
35   and the following description that, unless other notified, in addition to any combination of features belonging to one type of subject matter also any combination between features relating to different subject matters, in particular between

features of the method type claims and features of the appa-
ratus type claims is considered as to be disclosed with this
document.

5   The aspects defined above and further aspects of the present
invention are apparent from the examples of embodiment to be
described hereinafter and are explained with reference to the
examples of embodiment. The invention will be described in
more detail hereinafter with reference to examples of embodi-
10   ment but to which the invention is not limited.

Brief Description of the Drawings

Embodiments of the present invention are now described with
15   reference to the accompanying drawings. The invention is not
limited to the described or illustrated embodiments.

Fig. 1 schematically illustrates a wind turbine including a
nacelle with an arrangement for determining an inclination
20   angle according to an embodiment of the present invention;

Fig. 2 illustrates a graph as considered in a method of de-
termining an inclination angle of a wind turbine tower ac-
cording to an embodiment of the present invention which may
25   for example be performed by the arrangement illustrated in
Fig. 1.

Detailed Description

30   The illustration in the drawings is in schematic form.

Illustrated in **Fig. 1** is a wind turbine 100 according to an
embodiment of the present invention including a nacelle 105
with an arrangement 101 for determining an inclination angle
35   (relative to a vertical direction 104) of a wind turbine
tower 103 according to an embodiment of the present inven-
tion. The wind turbine 100 comprises a nacelle 105, the wind
turbine tower 103, the foundation 102, and rotor blades 107

connected to a not illustrated rotation shaft which drives a
generator to generate electric energy.

The arrangement 101 (here installed in the nacelle 105) com-
5   prises an accelerometer 109 and further a processor 111. The
accelerometer 109 is adapted to measure plural acceleration
values of an acceleration of the nacelle 105 in a predeter-
mined direction 113 (in the illustrated embodiment the longi-
tudinal direction of the nacelle) relative to the nacelle for
10   plural yawing position of the nacelle. The processor 111 is
adapted to derive the inclination angle 'Inc' based on the
plural acceleration values.

For adjusting the nacelle in the plural different yawing di-
15   rections or yawing positions, the nacelle 105 is turned
around (yawned around) the yawing axis 115 which substan-
tially runs along a longitudinal axis of the wind turbine
tower 103. The arrangement 101 is adapted to perform a method
of determining an inclination angle 'Inc' of the wind turbine
20   tower 103 by measuring plural acceleration values of an ac-
celeration of the nacelle 105 in a predetermined direction
113 relative to the nacelle 105 for plural yawing positions
Nac_pos of the nacelle 105 and by deriving the inclination
angle 'Inc' based on the plural acceleration values.
25
In Fig. 1, 'Ag' denotes the gravity acceleration (9.82 m/s²,
and 'Ay' is the acceleration measured by the accelerometer
111 in the direction 113 which is fixed relative to the na-
celle 105. 'Inc' is the maximum inclination in all nacelle
30   positions. 'Nac_pos' is the nacelle position (also called yaw
position) relative to North, i.e. an arbitrary direction.

The acceleration Ay is measured by the accelerometer 111 and
according to the method for determining the inclination an-
35   gle, the inclination is extracted from nacelle acceleration
measurements, while the turbine is performing for example a
cable untwist operation. The accelerometer 101 is for example
placed within or at the nacelle 105 to measure Ay according

to Fig. 1. The measured nacelle acceleration Ay can be expressed by:

$$Ay = Ag * \sin(Inc) * \sin(Nac\_pos+k) + offset + vibrations$$

Therein, 'offset' is the sensor offset which is steady over a shorter time and 'vibrations' are representing accelerations caused by movements of the tower. These vibrations have a zero mean value. While the turbine is performing a cable untwist, it may yaw more than one round which will give data points for Nac_pos from 0 to 360°.

According to an embodiment of the present invention, a binning method is utilized to reduce noise and vibrations and scatter in the measured acceleration data. By averaging A_y in bins of nacelle positions, the vibrations will be filtered out, as indicated by the next equation.

$$Ay\_filtered = BinData(Nac\_pos, Ay, 0:360) =\sim Ag * \sin(Inc) * \sin(Nac\_pos+k) + offset$$

The offset can be subtracted as it is the mean value of the binned data:

$$Ay\_UnBiased = Ay\_filtered - mean(Ay\_filtered) =\sim Ag * \sin(Inc) * \sin(Nac\_pos+k)$$

The inclination can then be calculated by applying an inverse of the sine function to the relation between the amplitude of this signal and the gravity acceleration:

Fig. 2 illustrates a graph in a coordinate system having an ordinate 201 indicating the nacelle positions in degree and having an ordinate 203 indicating the nacelle acceleration as measured by the accelerometer 111. The scatter points 205 represent the raw measured acceleration values of the nacelle 105 along the direction 113. The scattered data 205 comprise noise and vibrations and are filtered according to the em-

bodiments of the present invention to derive filtered acceleration values or averaged acceleration values 207. As can be appreciated from Fig. 2, the curve 207 resembles a sine curve shifted by a particular phase-shift. The phase-shift k in the equation above comprises information regarding the direction/orientation of the inclination angle. The amplitude A of the curve 207, i.e. half of the difference 2A between the maximum 209 and the minimum 211, is related to the inclination angle. By taking the inverse of half the difference 2A between the maximum 209 and the minimum 211 of the curve 207, the inclination angle Inc can be determined. The measured inclination can then be compared to a defined threshold and an alarm can be raised if the inclination exceeds this threshold. The accuracy of the method may be in the range of 0.01°.

Embodiments of the present invention may enable to monitor the inclination of the wind turbine tower and foundations without any manual operations. This may have the advantage during the takeover process after commissioning, where it has to be verified that the inclination is within the tolerance limits. It has also an advantage relative to continuously monitoring the inclination where an early warning can be set before for example a scaur projection on the foundation needs repair.

Compared to the manual methods which are conventionally employed with for example spirit levels, the embodiments of the present invention may save efforts and maintenance personnel and may not be dependent on the actual weather conditions.

The inclination monitoring function may be placed in the turbine controller or it can be done offline from a central workstation or in a park controller.

The signal processing by the for example processor 111 may also comprise a fitting procedure to fit a sine function to the raw or filter data instead of employing the binning method as detailed above.

A dual axis accelerometer (e.g. for measuring accelerations Ax and Ay in directions x and y) placed in the nacelle may provide even higher accuracy. In this case, the data may be
5   fitted to a model for example

$$Ay = Ag * sin(Inc) * sin(Nac\_pos+k)$$

$$Ax = Ag * sin(Inc) * cos(Nac\_pos+k)$$

10

The orientation of the inclination relative to North may by be extracted by finding the best fit of the parameter k to the data set. This might be useful for the foundation inspection planning.
15

The cable untwist may be forced so it is not necessary to wait for an untwisting event.

A monitoring function may check the inclination during every
20   cable untwist event and set a warning in the turbine lock in case of excessive inclination.

It should be noted that the term "comprising" does not exclude other elements or steps and "a" or "an" does not ex-
25   clude a plurality. Also elements described in association with different embodiments may be combined. It should also be noted that reference signs in the claims should not be construed as limiting the scope of the claims.

30

CLAIMS

1. Method of determining an inclination angle (Inc) of a wind
turbine tower (103) at which a nacelle (105) is mounted, the

5 method comprising:
       measuring plural acceleration values (Ay) of an accel-
eration of the nacelle (105) in a predetermined direction
(113) relative to the nacelle for plural yawing positions
(Nac_pos) of the nacelle (105);

10   deriving the inclination angle based on the plural ac-
celeration values.

2. Method according to the preceding claim, further compris-
ing:

15   measuring further plural acceleration values of an ac-
celeration of the nacelle in a further predetermined direc-
tion relative to the nacelle for the plural yawing positions
of the nacelle;
       deriving the inclination angle further based on the fur-

20 ther plural acceleration values.

3. Method according to one of the preceding claims, further
comprising:
       deriving an orientation/direction of the inclination of

25 the wind turbine tower (103) based on the plural acceleration
values (Ay).

4. Method according to one of the preceding claims,
wherein the deriving the inclination angle comprises:

30   averaging plural groups of the acceleration values asso-
ciated with plural yawing position ranges to obtain for each
yawing position range an associated averaged acceleration
value (207);
       deriving the inclination angle (Inc) based on the aver-

35 aged acceleration values.

5. Method according to the preceding claim, wherein the de-
riving the inclination angle comprises:

deriving a mean acceleration value by averaging the plural acceleration values over all yawing positions;

calculating plural acceleration differences (207) between the averaged acceleration values and the mean acceleration value;

determining a maximum (209) and a minimum (211) of the acceleration differences;

determining a difference between maximum and minimum and deriving an inverse of a trigonometric function using a quantity proportional to the difference as an argument, to obtain the inclination angle.

6. Method according to one of the preceding claims, wherein the deriving the inclination angle comprises:

fitting a trigonometric function, in particular cosine or sine function, on the plural acceleration values;

deriving the inclination angle (Inc) based on an amplitude of the trigonometric function.

7. Method according to one of the preceding claims, wherein the different yawing positions (Nac_pos) cover samples of one or more circumferences, in particular at least 360°, of a rotation of the nacelle around a axis (115) running along a longitudinal direction of the wind turbine tower.

8. Method according to one of the preceding claims, performed during a cable untwist operation.

9. Method according to one of the preceding claims, wherein the nacelle (105) is continuously rotated around a yawing axis while measuring the acceleration.

10. Method according to one of the preceding claims, wherein the predetermined direction (113) is substantially parallel to a longitudinal direction of the nacelle, the further predetermined direction is in particular substantially orthogonal to a longitudinal direction of the nacelle.

11. Method according to one of the preceding claims, wherein the measuring the plural acceleration values is performed using an accelerometer (109) installed at the nacelle (105).

12. Method of monitoring a wind turbine, comprising:

performing a method according to one of the preceding claims;

raising an alarm, in particular shutting down the wind turbine, if the determined inclination angle exceeds a threshold.

13. Arrangement (101) for determining an inclination angle (relative to a vertical direction) of a wind turbine tower at which a nacelle is mounted, the arrangement comprising:

an accelerometer (109) adapted to measure plural acceleration values (Ay) of an acceleration of the nacelle in a predetermined direction (113) relative to the nacelle (105) for plural yawing positions (Nac_pos) of the nacelle (105);

a processor (111) adapted to derive the inclination angle (Inc) based on the plural acceleration values (Ay, 205, 207).

14. Wind turbine, including:

a nacelle (105);

a wind turbine tower (103) having rotatable supported the nacelle (105) on top; and

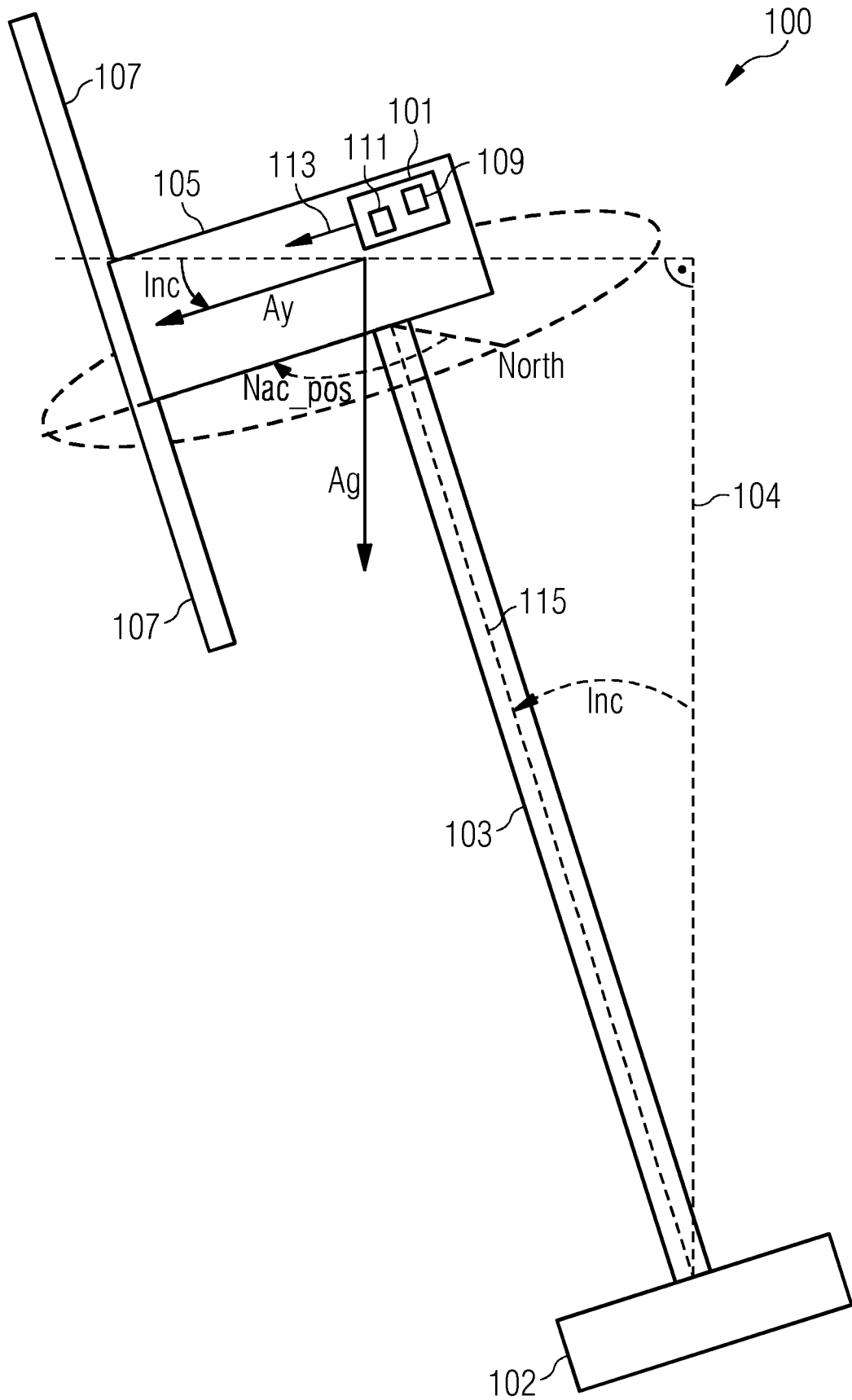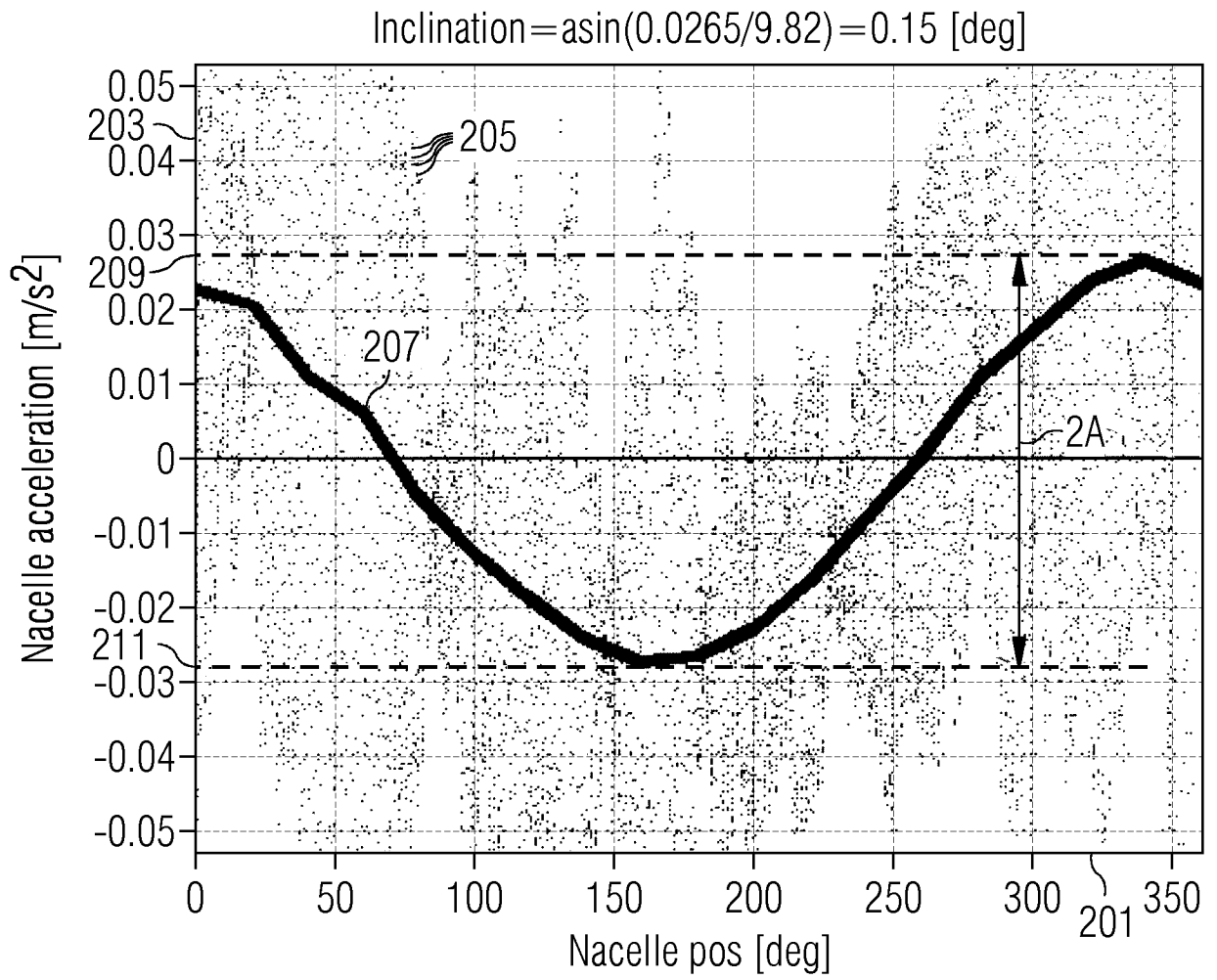an arrangement (101) according to the preceding claim.

FIG 1

FIG 2

Inclination=asin(0.0265/9.82)=0.15 [deg]

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

INV. F03D17/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F03D

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/316740 A1 (HEINING NILS [DE]) 23 October 2014 (2014-10-23)	1-7,9-14
A	paragraph [0007] paragraph [0014] paragraph [0016] paragraph [0028] claims 1,2,3,4,10; figure 1 -----	8

☐ Further documents are listed in the continuation of Box C.   ☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 October 2017	06/11/2017

Name and mailing address of the ISA/	Authorized officer
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1

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