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(54) **METHOD OF AUTOMATIC DETECTION OF SYNCHRONOUS RUBBING IN TURBINE**

VERFAHREN ZUR AUTOMATISCHEN ERKENNUNG EINER SYNCRHONREIBUNG IN EINER TURBINE

PROCÉDÉ DE DÉTECTION AUTOMATIQUE DE FROTTEMENT SYNCHRONE DANS UNE TURBINE

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Description

Field of the invention

[0001] The present invention relates to a method of automatic detection of a synchronous rotor-stator contact in operation of a turbine and relates to the field of measurement and evaluation of mechanical oscillations and resonances of turbine rotors. It may be applied for use in steam and gas turbines.

Background of the invention

[0002] During operation of the steam and gas turbines, an undesired contact between a rotor and a stator may occur in some situations (called "rotor-stator rub" or "rubbing"). Said situations may occur e.g., during run-up of the turbine when vibrations are usually highest while overcoming rotor natural frequencies. In the first phase of this contact, seals fitted between the turbine rotor and stator are brushed first due to which the amount of leaking medium increases and the turbine performance reduces. In the case the rotor-stator contact is not early detected and removed through a suitable intervention in the turbine operation, both the rotor and stator may get seriously damaged, or rub may lead to the turbine failure with consequent huge financial loss. Early contact removal may be achieved, for example, by change to the speed during the turbine run-up or run-down, or by change to lifting oil parameters in use of the turbine on a swivelling equipment.

[0003] The rotor-stator contact may be a partial, which refers to very short but at least several times repeated contact between the rotor and the stator, or a full-annular, which refers to continuous or almost continuous contact between the rotor and the stator. In doing so, the full-annular rotor-stator contact is always preceded, at least for a short moment, by the partial rotor-stator contact. At present, detection of the partial rotor-stator contact is based in particular on offline analysis of vibration signals, when the turbine operator monitors total level of the measured vibration, as well as phasor of a first harmonic component in the vibration signal. A phasor refers to visualisation of an amplitude of a harmonic signal and an initial phase with respect to a key-phasor (initiation of the rotor revolution) in a complex plane. In the case of a jump change in total vibrations or the phasor rotation of the first harmonic component with a time varying or periodically changing amplitude, the rotor-stator contact is detected, and a detailed data analysis is carried out after finishing the measurement to eliminate a possibility of false-positive detection. Therefore, this approach is inappropriate for the rotor-stator contact detection during real use of the turbine, and may be essentially employed only for laboratory or experimental purposes.

[0004] Another approach for detection of the partial rotor-stator contact is based on that, in addition to change to the phasor of the first harmonic component of the vibration signals, the contact is also accompanied by forming of sub-harmonic components of the spectrum, with frequency corresponding to frequency of the rotor-stator impacts. However, a disadvantage of the rotor-stator contact detection based on monitoring of such sub-harmonic components is that frequency of some of them are very close to the frequencies corresponding to manifestations of other defects, e.g., instability of oil film of a journal bearing. Consequently, there may be a false positive detection of the rotor-stator contact, or on the contrary, an erroneous evaluation of the manifestations of the contact as a defect of a different kind. Solution of the above problem is disclosed in EP 2,746,541, which proposes a method suitable for detection and localization of the partial rotor-stator contact in use of the turbine.

[0005] In addition, the patent and non-patent literature discloses other methods for detection and/or localization of the partial rotor-stator contact based on quite different principles. For example, EP 1,533,479 discloses a method for detection of the rotor-stator contact where operational parameters of the turbine, such as for example shell temperature, rotor eccentricity, condenser pressure, and generator load are monitored. In doing so, the applicable algorithm evaluates independently the change to individual values and in the case of an abnormal or a jump change of any of them, the change is evaluated as a symptom of the rotor-stator contact. A disadvantage of the method is that a jump change to a monitored value may relate to other phenomena or faults that normally occur in use of the turbine. Hence, there is very high likelihood of a false-positive rotor-stator contact detection. Considering the dynamics of the monitored values and foreseen sensitivity of the algorithm in use, the evaluation of change to these values followed by the rotor-stator contact detection may not be contemplated as a sufficiently fast method applicable in real in use of the turbine.

[0006] US 2008/240902 discloses a method for the rotor-stator contact detection that consists in monitoring of turbine stator temperature on at least of a part of circumference thereof. A local temperature increase, if any, is attributed to rubbing between the rotor and the stator, and evaluated as presence of the rotor-stator contact. The point of contact on the stator may be roughly localized based on placement of a temperature sensor that senses the temperature increase. A disadvantage of the procedure is that at the moment when sufficiently high heat amount is produced through the rubbing between the rotor and stator for the temperature sensor to detect it, up to order of minutes may lapse since rotor-stator contact origin. Over that time, the rotor, stator, or other turbine components may get heavily damaged, and the rotor bending is unpreventable in a manner other than the machine shut-down. Another disadvantage is that in case of more severe rotor-stator contact, which occurs along the full circumference of the stator or a larger part thereof, the stator temperature increase is in fact recorded evenly by most of or all temperature sensors placed in the stator. Owing to this, the rotor-stator contact is not always determined. A substantial disadvantage is that additional installation of a higher number of temperature sensors into the turbine stator body requires shutting down the turbine and high costs.

[0007] In addition, US 2009/0003991 discloses a method for the rotor-stator contact detection that consists in continuous measurement of blade clearance from stator and/or rotor blades height. A disadvantage of the method, similarly to previous case, is the necessity of additional installation of special sensors inside the turbine stator and related higher total costs. The contact between a rotor blade and stator may be detected by measuring the change of gap between the rotor blade and seal in the stator. Insofar as the clearances between the blade and stator are higher than clearance between a shaft and the stator, the rotor-stator contact primarily occurs on the turbine shaft. Real likelihood of successful and early detection of the rotor-stator contact in this way is very limited. Another disadvantage is possibility of false-positive detection of the rotor-stator contact in case of change to dimension sensed by the sensors, which may occur also for different reasons, e.g., due to rotor eccentricity, change to rotation speed, and more. Document US 2021/140851 discloses a system and a method for automatic diagnosis of a power generation facility. The system includes a data measuring unit for acquiring vibration data from a rotating body of a power facility, a signal processing unit for signal-processing acquired vibration data, and extracting and quantifying predetermined characteristic factors with respect to a time domain, a frequency domain, and a shape area. It further includes a characteristic pattern storage unit for storing a characteristic factor pattern classified for each failure type, and a failure diagnosis unit for diagnosing whether a power facility to be diagnosed has a failure. The failure type of the power facility, on the basis of a classified characteristic factor pattern, is determined.

[0008] Document US 4,478,082 discloses a method and an apparatus for detecting the occurrence of rubbing in a rotary machine. In this method, at least one acoustic sensor is mounted on at least the rotor part or the stator part of the rotary machine. The output signal from the acoustic sensor is detected and then filtered to extract a frequency component having a frequency substantially equal to the rotational frequency of the rotary machine. The purpose of these steps is to detect the occurrence of rubbing in the rotary machine as early as possible and also to locate the source of the rubbing. Even when the occurrence of abnormal metal-to-metal contact at a bearing of the rotary machine is detected, it is discriminated from rubbing so that the occurrence of the rubbing can be reliably detected.

[0009] The objective of the present invention is to propose a new method for detection of synchronous rotor-stator contact in use of a turbine, which eliminates the disadvantages of the prior art, and allows for the rotor-stator contact detection in real time as earliest as it occurs. In addition, the objective is to eliminate installation of new sensors inside the turbine body, or inside flow part of the machine, and use the existing (normally installed) sensors.

Summary of the invention

[0010] The present invention discloses a method of automatic detection of a synchronous rubbing in a turbine. It is applicable both for gas as well as steam turbine. For the method described herein, at least two sensors of rotor vibrations arranged on the turbine stator, perpendicularly each other within one measurement plane are used. The measurement plane is perpendicular to a rotor rotation axis. It means that the sensors measure one area of the rotor, of which points are at the same distance from ends of the rotor shaft. The described method for automatic detection of synchronous rubbing may be carried out on multiple points of a single rotor at the same time. It means that a plurality of measurement planes with relevant sensors of rotor vibrations are employed, wherein measured data is processed and evaluated separately for each measurement plane. A detection in a single of the employed measurement planes is enough to detect the synchronous rubbing. A plurality of the measurement planes is favourably employed for longer rotors where more accurate detection of the synchronous rubbing is achieved.

[0011] The method is carried out that each sensor continuously measures the relative distance of the rotating rotor and turbine stator in the place of the sensor. A trajectory of eccentric rotor motion in the measurement plane is reconstructed by combination of rotor distances filtered at rotational frequency (Ω) in an orthogonal coordinate system. The rotational frequency is denoted 1X, and sometimes also referred to as a first harmonic signal component. Furthermore, the trajectory of eccentric rotor motion is divided into individual orbits. Each orbit includes data per one rotor revolution, wherein the data includes information about the orbit origin coordinates in the orthogonal coordinate system for the beginning of the rotor revolution. In the case of perfectly centric rotor there should be no vibrations during rotor rotation, no eccentric motion of the rotor in the measurement plane would be measured by rotor vibration sensors, and no orbits would form. This is rather a theoretical case; in fact, vibrations and eccentric rotor motion are always detected.

[0012] An initial amplitude defined by the distance of the orbit origin from the origin of the orthogonal coordinate system is determined for each orbit. Then, an initial angle is defined by angle between straight line defined by the origin of the orthogonal coordinate system and the orbit origin and any axis having a known position in the orthogonal coordinate system. It is favourable if an axis having known position is the X axis or Y axis of the orthogonal coordinate system. The origin of the coordinate system lies in axis of non-vibrating rotor, or lies in the centre of a circle inscribed to the rotor journal bearing inside the stator.

[0013] Furthermore, the development of change to coordinates of the orbit origin over time is monitored by monitoring the changes of the initial amplitude and the initial angle between consecutive orbits. Of the measured values, the synchronous rubbing is detected by cumulative meeting of these indicators for a unit of time:

- development of change to the initial angle of opposite direction of the rotor rotation. It means that development of change to the initial angle is in the area of negative values for the counter clockwise rotation of the rotor, and in the area of positive values for clockwise rotation of the rotor;
- exceeding of the threshold value of the initial amplitude derivation;
- exceeding of the threshold value of the initial angle;
- exceeding of the threshold value of the area under curve, which is defined by the coordinates of the origins of the consecutive orbits.

[0014] Meeting of only of some of these 4 points may indicate an impending synchronous rubbing, however, the information is preliminary only. Evaluation of only some of these 4 points as synchronous rubbing would result in high number of false-positive detections which is not desired.

[0015] Generally, the primary excitation force acting on the rotating rotor is the centrifugal force which acts in the point of a residual unbalance of the rotor. The centrifugal excitation force is a harmonic function of time with frequency equal to the rotor rotational frequency. The point where the centrifugal force acts is known as Heavy Spot. Vibration response of the rotor to acting centrifugal force is the harmonic function of time that is phase-delayed with respect to the excitation force. A place on the rotor surface being steadily farthest from non-deflected (ideal) rotor centre, or from the origin of the orthogonal coordinate system, is referred to as High Spot. This place is angle-shifted counter the rotation direction when compared to the point of the centrifugal force. The shift angle size between High Spot and Heavy Spot depends on rotational speed of the rotor, and is defined by phase characteristics of a mechanical system. In the case when rub occurs due to excessive vibrations, it usually occurs in High Spot. In the case of the synchronous rubbing, which occurs periodically with each rotor revolution, there is transient temperature rotor bending caused by rubbing the stator and by local rotor temperature increase. The rotor bending may be interpreted as another unbalance, and a point of another centrifugal force is formed in the High Spot direction. Combining the centrifugal force acting in the point of original mechanical unbalance and the centrifugal force acting in the point of new temperature unbalance, a new effective centrifugal force is formed, which is, however, shifted compared to original centrifugal force acting in the point of the mechanical unbalance by angle α. The change of the initial phase of an excitation force acting on the rotor also invokes a change to the rotor response initial phase 1X because the angle formed between High Spot and Heavy Spot is defined for said rotor rotational speed by phase characteristic of the mechanical system. The amplitude of the resultant of the centrifugal forces will be higher or lower than the amplitude of original centrifugal force acting in Heavy Spot considering the mutual angle between the original centrifugal force and the centrifugal force with its point in High Spot. Change of the excitation force amplitude invokes corresponding change to the 1X amplitude of rotor vibration response. Should we assume that the synchronous rubbing occur in High Spot, we need to know phase characteristics of the rotor response in each measurement plane to decide how the rotor response changes in the rubbing in High Spot.

[0016] Let's assume that there is an acute angle between the centrifugal forces acting in the points of Heavy Spot and High Spot for said rotor rotational speed. In the case of occurrence of synchronous rubbing, the resultant of the original centrifugal forces and the centrifugal forces that occurred due to temperature rotor bending will have amplitude higher than amplitude of the original centrifugal force, and the initial angle of the 1X orbit origin will change counter the rotor rotation direction. The initial angle of the 1X orbit origin will change counter the rotation up to mutual 180° angle between the original centrifugal force and the centrifugal force in the High Spot.

[0017] The method described in the present invention assumes measurement of relative rotor vibrations in two mutually perpendicular directions. The angular position of the first of the sensors in the rotation direction with respect to the horizontal axis may be arbitrary φ_m (Fig. 1). Furthermore, a rotor key-phasor signal measurement is assumed. The rotor key-phasor is one specific point of the rotor in the measurement plane. Rotor key-phasor measurement is an assumption for dividing the measured signals into individual rotor revolutions. It is usually carried out by an induction sensor located on the turbine stator.

[0018] Then, the initial amplitude and the initial angle of the 1X orbit origin is evaluated for signals of the relative rotor vibrations, e.g., by applying the order spectrum calculation from said signals, or by estimation using the least squares method.

[0019] To detect the synchronous rubbing, the initial amplitude and the initial angle of the 1X orbit are monitored (Fig. 2). The initial amplitude and the initial angle of the 1X orbit origin are evaluated from the amplitudes and the initial 1X phases of both signals of the relative rotor vibrations:

$$A_c = \sqrt{(A_x \cdot cos\varphi_x)^2 + \left(A_y \cdot cos\varphi_y\right)^2}, \quad (1)$$

$$\varphi_c = atan\left(\frac{A_y \cdot cos\varphi_y}{A_x \cdot cos\varphi_x}\right). \quad (2)$$

[0020] The method of automatic detection of synchronous rubbing is based on evaluation of the following criteria (Fig. 3):

- exceeding of the determined threshold value of change to the initial amplitude of the 1X orbit origin for a selected unit of time;
- exceeding of the determined threshold value of change to the initial angle of the 1X orbit origin for a selected unit of time;
- exceeding of the determined threshold value of the curve area circumscribed by the origins of consecutive orbits for a selected unit of time;
- development of change to the initial angle of opposite direction of the rotor rotation for a time period limited by T[0] and T[n].

[0021] The threshold values for each criterion are determined as 400% of standard deviation of said quantity from a sufficiently long data line (at least 1 hour) in use without rubbing present. The determined time unit may be different for each criterion. The assumptions for use of the described method include turbine operation at constant speed and knowledge of phase characteristic of the system.

[0022] Owing to the present invention, it is possible to eliminate installation of new sensors inside the turbine body, or inside flow portion, and the existing (normally installed) sensors may be used. This substantially cheapens the installation of the monitoring system of the synchronous rubbing and increases availability of long-term monitoring not only for newly installed turbines but also for machines already in use (no machine shutting down is necessary when installing the monitoring device).

Description of drawings

[0023] The exemplary embodiment of the proposed technique is described with reference to the drawings, on which

Fig. 1 - is a scheme of possible position of sensors of the rotor vibrations against the rotor with indication of the sense of rotor rotation while measuring the relative rotor vibrations;
Fig. 2 - filtered 1X orbit with the illustrated origin of the orbit;
Fig. 3 - characteristics for development of quantities for detection of the synchronous rubbing;
Fig. 4 - course of the initial amplitude and of the initial angle of the 1X orbit origin in the presence of the synchronous rubbing;
Fig. 5 - detection criteria of synchronous rubbing with indicated threshold values;
Fig. 6 - the detected presence of synchronous rubbing identified, marked in bold (exceeding of all three threshold values and development of change to the initial angle counter the rotor rotation direction).

Exemplary embodiment of the invention

[0024] Two sensors of the rotor vibrations are used in this exemplary method of the automatic detection of synchronous rubbing in the steam turbine. The sensors are arranged on the steam turbine stator perpendicularly each other within a single measurement plane perpendicular to the steam turbine rotor axis of rotation. Each sensor continuously measures the relative distance of the rotating rotor and the steam turbine stator in the place of the sensor. In this example, the rotor rotates counter clockwise. A trajectory of eccentric rotor motion in the measurement plane is reconstructed by combination of rotor distances filtered at rotational frequency 1X in an orthogonal coordinate system. Furthermore, the trajectory of rotor motion is divided into individual orbits. Each orbit includes data per one rotor revolution, wherein the data includes information about orbit origin coordinates in an orthogonal coordinate system.

[0025] An initial amplitude defined by distance of the orbit origin from the origin of the orthogonal coordinate system is determined for each orbit. Furthermore, an initial angle is defined for each orbit by angle between a straight line defined by the origin of the orthogonal coordinate system and the orbit origin and any axis having a known position in the orthogonal coordinate system. In this case, the X axis of the orthogonal coordinate system is the axis.

[0026] Furthermore, the development of change of the orbit origin coordinates over time is monitored so that the change of the initial amplitude value and change of the initial angle between the consecutive orbits are monitored. The synchronous rubbing is detected by the development of change to the initial angle counter the rotor rotation direction (counter clockwise in this example - the area of positive values) and by exceeding of threshold values of derivation of the initial amplitude, initial angle, and area under curve being defined by the coordinates of the origins of the consecutive orbits.

[0027] In this example, the threshold values are:

- initial amplitude: 0.12 [μm/min]
- initial angle: -0.0168 [rad/min]
- area under curve: 0.1 [μm^2] while assuming the orbit initial point curve in 1 minute.

Claims

1. A method of automatic detection of synchronous rubbing in a turbine, wherein at least two rotor vibration sensors arranged on a turbine stator perpendicularly each other within a single measurement plane perpendicular to the turbine rotor axis of rotation are used, wherein each sensor continuously measures the relative distance of the rotating rotor and the turbine stator in the place of the sensor, wherein a trajectory of eccentric rotor motion in the measurement plane is reconstructed from the measured distances filtered at the rotation frequency by combination in an orthogonal coordinate system, and dividing the rotor axis motion trajectory into individual orbits is made, where each orbit includes data for single rotor revolution, wherein the data includes information about the orbit origin coordinates in an orthogonal coordinate system at the beginning of the rotor revolution,

    and an initial amplitude defined by the distance of the orbit origin from the origin of the orthogonal coordinate system is specified for each orbit, and an initial angle is defined for each orbit by an angle between a straight line defined by the origin of the orthogonal coordinate system and orbit origin and any axis having a known position in the orthogonal coordinate system,
    and the development of change to coordinates of the orbit origin over time is monitored, **characterized in that** the development of the orbit origin coordinates change over time is monitored by monitoring the change of the initial amplitude value and change of the initial angle between the consecutive orbits, wherein the synchronous rubbing is detected by the development of change of the initial angle counter the rotor rotation direction and by exceeding of threshold values of the initial amplitude, initial angle, and the area under curve defined by the coordinates of the origins of consecutive orbits, in a determined unit of time.

Patentansprüche

1. Verfahren zur automatischen Erkennung synchronen Reibens in einer Turbine, wobei mindestens zwei Rotorschwingungssensoren, die auf einem Turbinenstator senkrecht zueinander innerhalb einer einzigen Messebene senkrecht zur Rotationsachse des Turbinenrotors angeordnet sind, verwendet werden, wobei jeder Sensor kontinuierlich den relativen Abstand des rotierenden Rotors und des Turbinenstators an der Stelle des Sensors misst, wobei ein Bewegungspfad der exzentrischen Rotorbewegung in der Messebene aus den gemessenen Abständen, die bei der Rotationsfrequenz gefiltert sind, durch Kombination in einem orthogonalen Koordinatensystem rekonstruiert wird, und die Aufteilung der Bewegungsbahn der Rotorachse in einzelne Bahnen vorgenommen wird, wobei jede Bahn Daten für eine einzelne Rotorumdrehung enthält, wobei die Daten Informationen über die Koordinaten des Bahnursprungs in einem orthogonalen Koordinatensystem zu Beginn der Rotorumdrehung enthalten,

    und eine ursprüngliche Amplitude, die durch den Abstand des Bahnursprungs vom Ursprung des orthogonalen Koordinatensystems definiert ist, für jede Bahn angegeben wird, und ein ursprünglicher Winkel für jede Bahn durch einen Winkel zwischen einer geraden Linie, die durch den Ursprung des orthogonalen Koordinatensystems und den Bahnursprung definiert ist, und einer beliebigen Achse mit einer bekannten Position im orthogonalen Koordinatensystem definiert ist,
    wobei die Entwicklung der Veränderung der Koordinaten des Bahnursprungs im Laufe der Zeit überwacht wird, **dadurch gekennzeichnet, dass**
    die Entwicklung der Änderung der Koordinaten des Bahnursprungs im Laufe der Zeit überwacht wird, indem die Änderung des ursprünglichen Amplitudenwerts und die Änderung des ursprünglichen Winkels zwischen den aufeinanderfolgenden Bahnen überwacht wird, wobei das synchrone Reiben durch die Entwicklung der Änderung des ursprünglichen Winkels entgegen der Rotordrehrichtung und durch das Überschreiten von

Schwellenwerten der ursprünglichen Amplitude, des ursprünglichen Winkels und der Fläche unter der Kurve, die durch die Koordinaten der Ursprünge der aufeinanderfolgenden Bahnen definiert ist, in einer bestimmten Zeiteinheit erkannt wird.

Revendications

1. Méthode de détection automatique de frottements synchrones dans une turbine, dans laquelle méthode on utilise au moins deux capteurs de vibrations du rotor perpendiculairement disposés sur le stator de la turbine dans un seul plan de mesure perpendiculaire à l'axe de rotation du rotor de la turbine, chaque capteur mesurant en continu la distance relative entre le rotor en rotation et le stator de la turbine à l'emplacement du capteur, et dans lequel endroit une trajectoire du mouvement excentrique du rotor dans le plan de mesure est reconstruite à partir des distances mesurées filtrées à la fréquence de rotation par combinaison dans un système de coordonnées orthogonales et par division de la trajectoire du mouvement de l'axe du rotor en orbites individuelles, chaque orbite comprenant des données d'une seule révolution du rotor, lesquelles données comprennent des informations sur les coordonnées d'origine du système de coordonnées orthogonales de l'orbite au début de la révolution du rotor,

   et une amplitude initiale définie par la distance de l'origine de l'orbite à partir de l'origine du système de coordonnées orthogonales est spécifiée pour chaque orbite, et un angle initial est défini pour chaque orbite par un angle entre une ligne droite définie par l'origine du système de coordonnées orthogonales et l'origine de l'orbite et tout axe ayant une position connue dans le système de coordonnées orthogonales,
   et l'évolution des changements aux coordonnées de l'origine de l'orbite est suivie au fil du temps, **caractérisé par le fait que**
   par la surveillance des changements de la valeur d'amplitude initiale et de l'angle initial entre les orbites consécutives d'où le frottement synchrone est détecté par l'évolution du changement de l'angle initial dans le sens inverse de la rotation du rotor et par le dépassement des valeurs de seuil de l'amplitude initiale, de l'angle initial et de l'aire sous la courbe définie par les coordonnées de l'origine des orbites consécutives, et ce, dans une unité de temps déterminée.

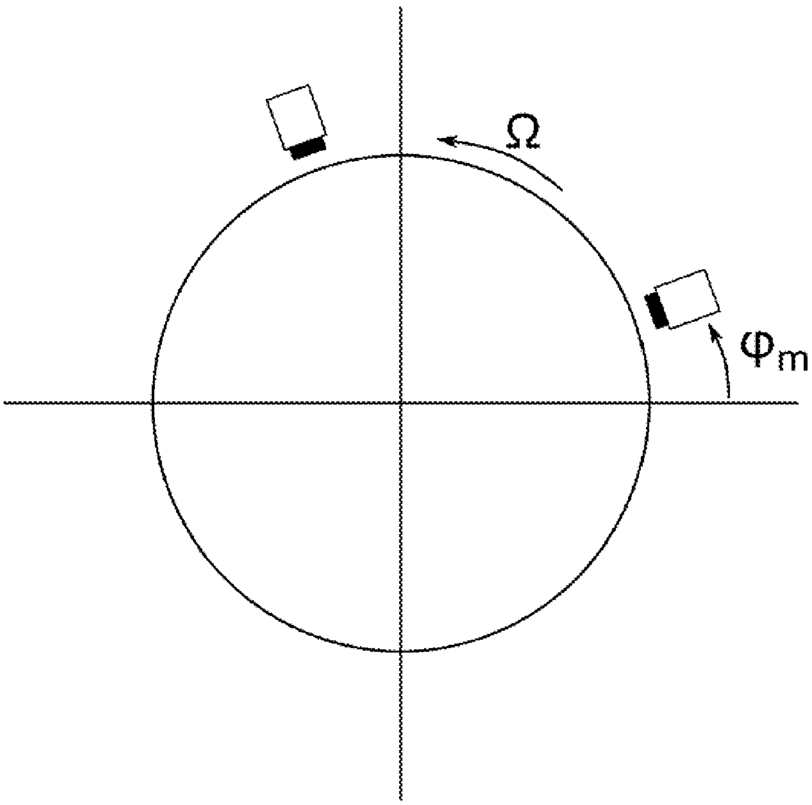

Fig. 1

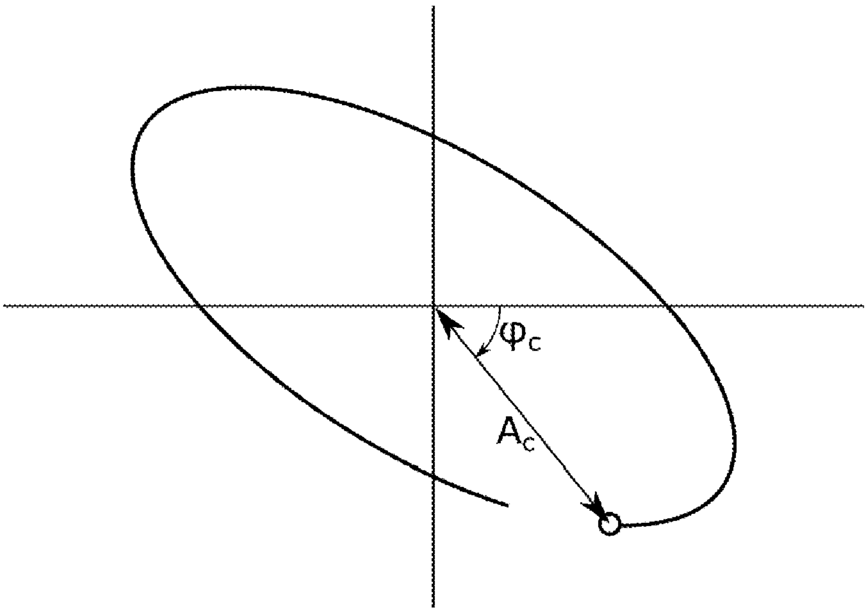

Fig. 2

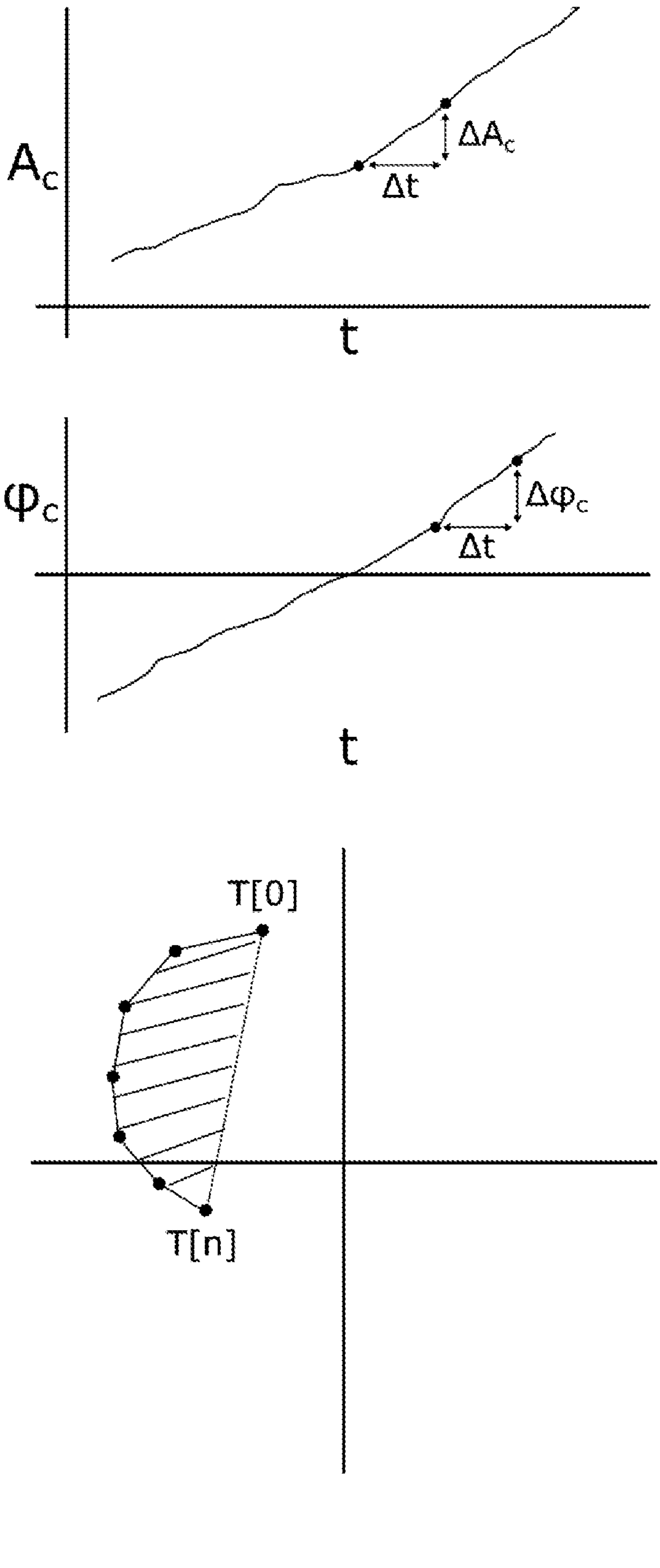

Fig. 3

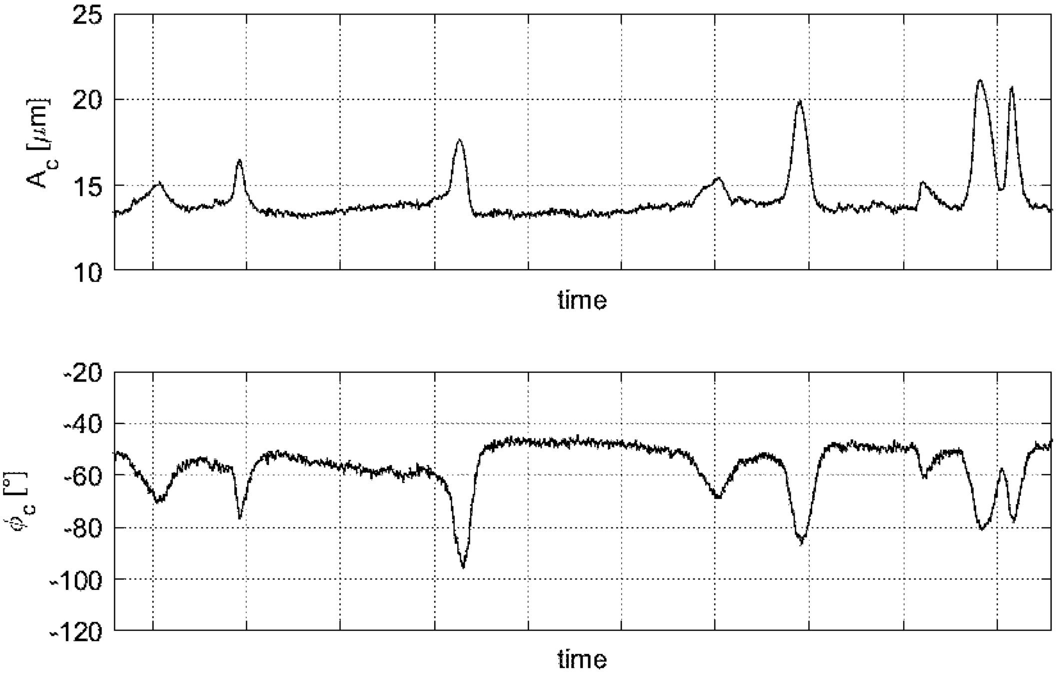

Fig. 4

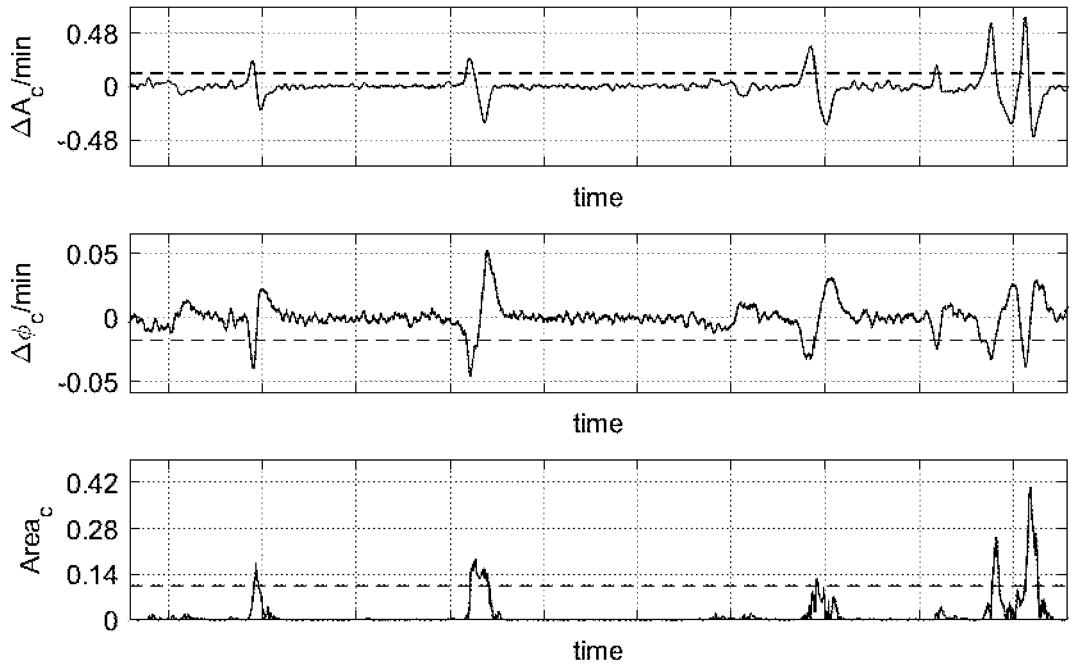
0.48
0
-0.48
ΔA_c/min
time
0.05
0
-0.05
Δφ_c/min
time
0.42
0.28
0.14
0
Area_c
time

Fig. 5

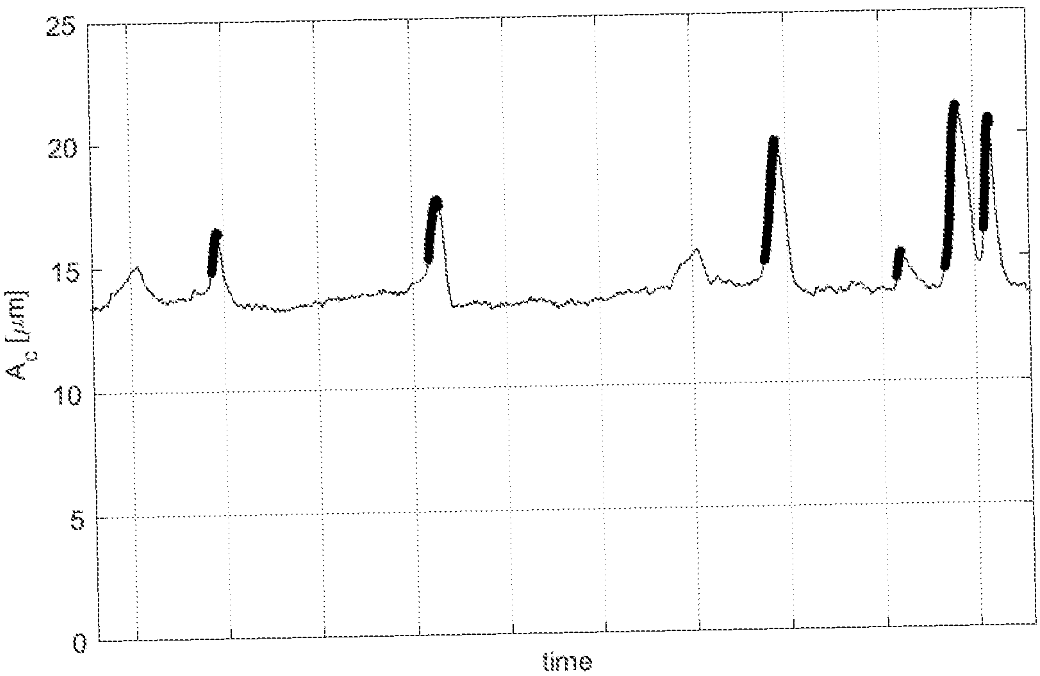

Fig. 6

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