

SYSTEM AND METHOD FOR MONITORING MECHANICALLY COUPLED STRUCTURES

Description

The invention concerns a system for monitoring a mechanically coupled structure and a corresponding method.

Sensors are known, which - for example based on the Sagnac effect - determine rotations absolutely and are therefore usable for recording the dynamical behaviour of large mechanically coupled structures under the influence of external forces independent of local reference frames. However, due to unavoidable drift in these sensors the frequency range is limited from below.

Therefore, it is a goal of the invention to provide a system and a method for monitoring mechanically coupled structures, which make monitoring of chronological sequences of the behaviour of mechanically coupled structures possible.

To achieve this goal the invention provides a system with the features of claim 1 and a method with the features of claim 6.

Preferred embodiments of the system and the method are provided by the dependent claims, respectively.

In the following the invention will be discussed with respect to embodiments and on reference to the figures. The figures illustrate:

- FIG. 1** a schematic illustration of a system during monitoring of a mechanically coupled structure according to an embodiment;
- FIG. 2** a schematic illustration for determining the orientation of the sensor to Earth's rotation axis;
- FIG. 3** a schematic illustration of a process flow of a method according to a further embodiment;

- FIG. 4** a system for monitoring according to a further embodiment;
- FIG. 5** the schematic structure of a system according to a further embodiment;
- FIG. 6** the schematic structure of a system according to a further embodiment;
- FIG. 7** the schematic structure of a system according to a further embodiment; and
- FIG. 8** a schematic process flow of a method according to a further embodiment.

In the figures structures and structural elements corresponding to each other are referred to with the same reference signs.

In FIG. 1 a system 100 for monitoring a mechanically coupled structure 101 is illustrated that includes a first sensor 102, which is configured to determine its orientation relative to Earth's rotation axis at predetermined times as a first measurement wherein the first sensor 102 is connectable with a first part of the mechanically coupled structure. Moreover, at least one second sensor 104 is provided, which has a known first orientation to the first sensor 102 at startup of the system 100 and is configured to determine a rotation rate and/or an acceleration as a second measurement. At the same time, the at least one second sensor 104 is connectable with one second part of the mechanically coupled structure. Moreover, a central unit 106 is provided as well as a communication network 108 over which the central unit 106 is connected to the first sensor 102 and the second sensor 104. The first sensor 102 is thereby configured such that the first measurements are transmitted to the central unit 106 and the second sensor 104 is configured such that the second measurements are transmitted to the central unit 106. The central unit 106 is configured to monitor the mechanically coupled structure 101 by means of the first and the second measurements.

The first sensor 102 may for example be formed as a Sagnac sensor or a Coriolis sensor. Both types of sensors are able to detect their orientation relative to Earth's rotation axis via the Sagnac effect and the Coriolis effect, respectively.

The communication network 108 may be formed wireless or wire-bound. Optical communication via optical fibre cables or via free space propagation is possible in this case as well as electric or electromagnetic communication. In this process, any communication paths between the sensors 102, 104 and the central unit 106 may be possible. For example, a direct unidirectional communication between the single sensors 102, 104, respectively, and the central unit 106 may be provided as a communication path which is particularly easy to implement. But also more complex communication paths like a bidirectional communication between the single sensors 102, 104 as well as between each of the sensors 102, 104 and the central unit 106 are possible.

If necessary the system may be improved by providing GNSS (Global Navigation Satellite System) sensors technology, which is not illustrated), as for example GPS (Global Positioning System), Galileo or Glonass in the sensors 102, 104, and then a measurement of the absolute position of the sensors 102, 104 is possible. Furthermore, using a fixed connection of antennas of the GNSS to the sensors 102, 104 it is possible to draw conclusions about rotations of the antennas (inclination or torsion) of the GNSS by the measurements of the sensors 102, 104, which would be not readily possible by satellite navigation alone. The antennas of the GNSS may also be used for determining translations.

In FIG. 2 it is schematically illustrated how the first sensor 102 on Earth's surface 200 is inclined by a given angle θ with respect to Earth's rotation axis 202.

By the system of the present invention long time observations on mechanically coupled structures are possible by comparing the measurements with the value of the projection of the known and constant Earth's rotation rate on the sensitive sensor axis of one of the sensors 102, 104. The reference to Earth's rotation axis 202 provides at the same time a criteria for avoiding a measurement error (false alarm), as the measurement is always correlated to Earth's rotation rate. If this is not the case normally a measurement error has occurred.

By the fixed reference of the first sensor 102 to Earth's rotation axis 202 it is possible to filter a long time drift, which enables also long time measurements, such as the detection of landslides, settlement of buildings, etc..

The second sensor 104 may be formed as rotation sensor, which has less precision for determining the orientation to Earth's rotation axis compared to the first sensor 102, whereby the system can be formed reasonably priced. The first sensor 102 may for example have a precision of $0.01^\circ/\text{hour}$ or better, while the second sensor may only have a precision of $1^\circ/\text{hour}$.

A mechanically coupled structure 101, which is monitored with the system and the method of the present invention, respectively, may be a structure, for which it is important to determine whether the orientation of single parts with respect to each other is changing, for example a building, a bridge, a ship, an airplane or a machine. While it is important for the aforementioned structure to detect any movements with respect to each other reliably in order to determine damages - e.g. after an earthquake - there are also mechanically coupled structures known, whose parts are allowed to move into specific allowed directions. For example, the rotor of a wind turbine is allowed to perform a rotational movement with respect to the stator. Rotating unbalance of the rotor, which leads to an additional linear component of movement of the rotor, should however be detected, allowing for a repair of the wind turbine if necessary. Also parts of Earth's surface (such as mountainsides, but also continuously connected parts of the earth crust) may be viewed as mechanically coupled structures.

FIG. 3 illustrates a schematic process flow of a method of the present invention. In that method in a first step S300 the orientation of the first sensor 102 with respect to Earth's rotation axis 202 is determined.

Afterwards, the orientation is transmitted to the central unit 106 in a step S302. By means of the second sensor 104 the rotation rate or acceleration of the second sensor 104 is determined in a step S304, wherein at startup of the system 100 the at least one second sensor 104 has a known first orientation to the first sensor 102. Afterwards, the measured rotation rate or acceleration of the at least one sensor 104 is transmitted to the central unit 106 in a step S306. Afterwards, in a step S308 a monitoring value is generated from the transmitted orientation of the first sensor 102 and the rotation rate or acceleration of the at least one second sensor 104, the monitoring value being used to monitor the mechanically coupled structure 101.

In a hybrid sensor system 400 as illustrated in FIG. 4 two or more rotation rate sensors 102, 402 can capture changes of state (e.g. deformations) of a mechanical

overall structure 403 or of parts of the mechanically coupled structure relative to each other, based on the Sagnac effect, the Coriolis effect and the inertia effect with different resolutions and with their relative reference to each other. In doing so, the highly resolving first sensor 102, also called central sensor or master, provides the external reference to the earth rotation vector 202 of the earth 200 as a fixed reference, while more simple (less exact) sensors 402 or slaves capture only the local reference to the master 102 as a function of time. In doing so, the sufficient sensitivity of the slaves for rotation measurements is used. The inferior sensitivity for the orientation of the slaves relative to the position of Earth's rotation axis 202 is then irrelevant. Thus, the different characteristics of the single sensors are transferred to each other (e.g. the absolute reference of the Sagnac effect to the Coriolis effect sensor or the inertia effect sensor, respectively). The central unit 106 is not illustrated, it may be connected with one of the illustrated sensors 102, 402 for transmission of measurements, or may be for example housed with the first sensor 102 (or with one of the second sensors 402) in a common casing.

With such a system loads on buildings or damages on buildings can be determined for example over deformations, which have been caused by earthquakes for example. The deformation of the structure gives a primary measurement, is present before damage, and can be used for quantitative ad hoc judgement of the potential of damage of a load. In this concept the first sensor 102 and the several second sensors 402 are firmly connected with the basic structure of a building 403. As the first sensor 102 can capture rotations absolutely based on the Sagnac effect the orientation of the building relative of the rotation axis 202 of the earth 200 is determined automatically, before, during and after an earthquake in real time. This allows the determination of the change of orientation of a building, which may have changed due to influences of a force, such as an earthquake or similar, without the need for local references.

According to FIG. 5 a further hybrid sensor system 500 can be formed which is formed from two or more rotation rate sensors 102, 402, 504 based on the Sagnac effect, the Coriolis effect, and the inertia effect with different resolutions and their relative reference to each other. Thereby, changes in the arrangement of parts of a totally or partly moveable mechanical overall structure or of parts 502, 506 of a totally or partly moveable mechanically coupled structure in relation to each other are captured. In doing so the highly resolving central sensor 102 (master) provides the external reference to the earth rotation axis 202 of the earth 200 as fixed

reference, while the simpler sensors 402, 504 captured the local reference to the master 102 dynamically as a function of time. Thus, the measurement method is applicable as method of inertia measurement for the relative movement of different mechanically coupled structures 502, 506 (e.g. parts of machines) with moveable components relative to each other, also if no optical, electrical or mechanical connection between these parts can be provided. Thus, the different characteristics of the single sensors 102, 402, 504 are transferred to each other (e.g. absolute reference of the Sagnac effect to Coriolis effect sensor and inertia effect sensor). The system is therefore applicable for monitoring of non-allowed movements in a system in which parts of a mechanical structure are allowed to move with respect to each other in a predetermined range (allowed movement).

According to FIG. 6 a further hybrid sensor system 600 can be given, which includes at least one accelerometer 604 (in FIG. 6 three of such accelerometer 604 are illustrated), wherein the sensors 102, 604 are attached to a mechanically coupled structure together or are attached on Earth's surface 602 and are therefore able to determine ground and structure characteristics, respectively (tomography, exploration). In this case the relation is used that the measured rotation rate $\dot{\Omega}$ and the transversal acceleration a of an excitation signal (e.g. a seismic wave) are in phase in an homogeneous medium and that the proportionality of these signals, independently captured of each other, correspond to the phase velocity c as shown in equation (1):

$$\dot{\Omega}(x,t) = -\frac{a(x,t)}{2c} \quad (1)$$

The phase velocity c (an apparent phase velocity in a heterogeneous medium as ratio of the rotation rate $\dot{\Omega}$ and the acceleration a) is changing significantly with the ground conditions (granite has a specific phase velocity for example) so that by means of these systems an exploration can be carried out. Hence, it is possible to search for deposits with a portable device and it is possible to analyze the time dependence by a fixedly installed network of sensors, respectively.

According to the embodiment of the system 700 illustrated in FIG. 7 the first sensor or master sensor 102 and the second or secondary sensors 104 are bidirectionally connected with each other on the basis of a self-organizing network and communicate across the network. This reduces the needed transmission power per

sensor and facilitates the enlargement/reduction of the network, as no interventions of a user are necessary. In this process, the first sensor 102 is connected to the central unit 106. The central unit 106 provides important functions for data usage and interpretation like the receiving of sensor data, a determination of time ("time stamping") (GPS, radio clock or the like), control of the sensors (e.g. switch on/off, range switching), an analysis (e.g. finite differences, phase relations, direction determination, threshold detection, noise elimination, sensor integrity examination, drift correction) and if necessary an alarm when a threshold is exceeded in early warning applications. At a deformation of the mechanically coupled structure 101, which is measured by the sensors 102, 104 and detected by the central unit 106, the integrity of the sensors 102, 104 can be guaranteed by a finite difference calculation and the degree of deformation can be determined.

Provided that the slave sensors have not moved from their original location/arrangement, their inertial measurements, which get less precise in the course of time, can be recalibrated.

This can be carried out on the one hand by exact initial measurement of the location/arrangement and if necessary the positions of the sensors relative to Earth's rotation axis at the begin of startup and by storing at a time t_0 the averaged single measurement values, which are then newly displayed, on the other hand by comparison of the measurements after an advanced time t_1 (for example after a predetermined time interval after startup of the system, if necessary repeatedly after predetermined time intervals) with measurements of the master sensor which generates smaller measurements error over time because of his higher precision. The first method can be used for all kinds of rotation sensors, therefore also for those which are due to their limited precision not able to resolve earth rotation rate as measurement value reference signal themselves. The second method raises in this case the integrity of the self-calibration method considerably, as a check of plausibility with the actual conditions in the spatial proximity of the single slave sensors is carried out via current measurements of the master sensors.

One has to take into account that for a successful self-calibration no event should have happened which changes the original location/arrangement of the slave sensor. This information is given in realistic cases (earthquake, abrupt change of position) mostly directly in the data of the slave sensors.

A further possibility is the self-calibration of the slave sensors, which have themselves the capability to measure Earth's rotation rate as a reference signal with sufficiently high precision. Then, the slave sensor can self-consistently initiate self-calibration against the original values of Earth's rotation rate measurement in case a tolerance threshold of the drift values is exceeded in the course of time. Also the master sensor would have to perform this procedure after a longer time period, in order to maintain stable drift values over very long time periods.

At this point the comparison to current master measurements can again increase the integrity of the method considerably.

As already discussed it is also possible that the central unit 106 is housed with the first sensor 102 or even one of the second sensors 104 together in a casing.

A time reference can be provided by using a clock as time measurement device 702, 704 at single sensors 102, 104 or also by a via the radio communication with a guaranteed low latency time (specification of the transmission protocol), wherein the assignment of times (per clock) can be carried out at the central unit 106 for each single sensor 102, 104.

The time references is for example used to get a chronological sequence of the processes and to bring the measurements determined at different times in relation to each other. In this way the spread of damages over time can be determined and moreover conclusion over the integrity of the system can be drawn. For example can be assumed that in the case of a proceeding spread of an offset of parts of a mechanically coupled structure 102 all sensors 102, 104 connected with the mechanically coupled structure 101 acquire the orientation and acceleration change, respectively, in an expected chronological sequence, which depend on the respective position of the sensors 102, 104. In case single sensors 102, 104 measure a time dependence of the orientation or acceleration, respectively, differing therefrom it can be assumed that a measurement error has occurred.

According to FIG. 8 a process is illustrated in a process flow diagram for which in a step 800 a change of structure of the mechanically coupled structure 101 occurs, e.g. by an earthquake. In a step 802 a change of rotation rate, a change of rotation angle (deflection), a change of acceleration or a change of orientation results which is read out in the step S804 over the first sensor 102. Afterwards in a step S806 the

comparison of the measured value with a nominal value of a configuration file is carried out. If necessary, in a step S808 read out of the second sensors 104 is carried out, which are for example arranged in a sensor array. In a step S810 a signal processing is carried out afterwards, for example a filtering or noise reduction or drift reduction, respectively. During signal processing, a determination of time-dependent frequency spectra from the chronological sequence of the transmitted first and second measurements may also be carried out. As it is possible to obtain time exact series of measurements of all first and second sensors 102, 104, all those time-dependent frequency spectra can be generated, which characterize the mechanically coupled structure and it is possible to deduce from changes in these frequency spectra changes and damages, respectively, in the mechanically coupled structures. Such functionality can serve as an early warning function.

In a following step S812 changes of the rotation rate and if necessary an acceleration are determined. By a comparison with a master sensor 102 in a step S814 changes between the first sensor 102 and the second sensor 104 are calculated whereby for example deformations can be recognized. Moreover, the integrity of data is examined, in order to avoid measurement errors. In case of security relevant conditions an alarm function is initiated. In a step S816 a protocol file is generated afterwards and files may be transmitted to a control station and an early warning function may be activated, respectively. Afterwards, the master sensor 102 is read out again in step S804 and the monitoring of the mechanically coupled structure 101 is carried out anew.

Claims

1. System for monitoring a mechanically coupled structure (101, 403, 502, 506, 602) with

a first sensor (102) configured to determine at predetermined times its orientation relative to Earth's rotation axis (202) as a first measurement, wherein the first sensor (102) is connectable with a first part of the mechanically coupled structure (101, 403, 502, 506, 602),

at least one second sensor (104, 402, 504, 604), which has a known first orientation to the first sensor (102) at startup of the system and which is configured to determine a rotation rate or an acceleration as a second measurement, wherein the at least one second sensor (104, 402, 504, 604) is connectable with a second part of the mechanically coupled structure (101, 403, 502, 506, 602),

a central unit (106), and

a communication network (108) over which the central unit (106) is connected with the first sensor (102) and the second sensor (104, 402, 504, 604),

wherein the first sensor (102) is configured to transmit the first measurement to the central unit (106), the second sensor (104, 402, 504, 604) is configured to transmit the second measurement to the central unit (106), and the central unit (106) is configured to monitor the mechanically coupled structure (101, 403, 502, 506, 602) by means of the first and second measurements.

2. System according to claim 1, characterized in that

the at least one second sensor (104, 402, 504, 604) is formed as rotation sensor which has compared to the first sensor (102) less precision for determining the orientation of Earth's rotation axis (202).

3. System according to claim 2, characterized in that

the first sensor (102) and the second sensor (104, 402, 504, 604) comprise a time measurement unit (702, 704) and transmit the first and second measurements together with the times at which the measurements were taken to the central unit (106) and

that the central unit (106) is configured to determine a chronological sequence of the orientation of the first sensor (102) and the second sensor (104, 402,

504, 604) to each other from the transmitted measurements and the transmitted times.

4. System according to claim 1,
characterized in that

the at least one second sensor (104, 402, 504, 604) is formed as acceleration sensor.

5. System according to any one of claims 1 to 4,
characterized in that

the first sensor (102) and the at least one second sensor (104, 402, 504, 604) are attached at different positions to the monitored mechanically coupled structure (101, 403, 502, 506, 602).

6. System according to any one of claims 1 to 5,
characterized in that

the communication network (108) is configured for bidirectional direct communication between the sensors (102, 104, 402, 504, 604).

7. System according to any one of claims 1 to 6,
characterized in that

the second sensor (104, 402, 504, 604) is configured to be recalibrated on the basis of the measurements of the first sensor (102) after a predetermined time interval after startup of the system.

8. Method for monitoring of mechanically coupled structures (101, 403, 502, 506, 602) comprising the following steps:

determining at predetermined times the orientation of a first sensor (102) relative to the Earth's rotation axis (202) by means of the sensor (102) as a first measurement,

transmitting the first measurement to a central unit (106),

determining a rotation rate or acceleration of at least one second sensor (104, 402, 504, 604), which has a known first orientation to the first sensor (102) at startup of the system as a second measurement,

transmitting the second measurement to the central unit (106),

generating a monitoring value from the first and the second measurement.

9. Method according to claim 8,
characterized in that

the second sensor (104, 402, 504, 604) measures his change of orientation independently from the transmitted orientation of the first sensor (102) and a change of the position of the second sensor (104, 402, 504, 604) with respect to the position of the first sensor (102) is determined by means of the transmitted orientation of the first sensor (102)

10. Method according to any of claims 8 or 9,
characterized in that

the first sensor (102) and the second sensor (104, 402, 504, 604) are each attached at different parts of a mechanically coupled structure (101, 403, 602), wherein the different parts are unmoveably mechanically coupled with respect to each other.

11. Method according to any of claims 8 or 9,
characterized in that

the first sensor (102) and the second sensor (504) are each attached at different parts (502, 506) of a mechanically coupled structure (502, 506), wherein the different parts (502, 506) are moveably mechanically coupled with respect to each other,

the respective different parts (502, 506) can perform movement with respect to each other allowed by the mechanical coupling, and

the monitoring value determined from the central unit (106) indicates whether one of the allowed or non-allowed movements between the different parts (502, 506) is present.

12. Method according to any of claims 8 or 9,
characterized in that

vibration excitations are impressed from outside on the mechanically coupled structure (101, 403, 502, 506, 602),

the second sensor (604) is formed as translation sensor and the apparent phase velocity of the measured vibration in the mechanically coupled structure (101, 403, 502, 506, 602) is determined from the measured orientation of the first sensor (102) and the measured acceleration of the translation sensor (604).

13. Method according to any of claims 8 to 12, characterized in that

the central unit (106) detects a measuring error in case the measurement of the first sensor (102) does not contain Earth's rotation rate.

14. Method according to any of claims 8 to 13, characterized in that

the central unit (106) determines time-dependent frequency spectra from a chronological sequence of the transmitted first measurements and the transmitted second measurements and generates a further monitoring value from the frequency spectra.

15. Method according to any of claims 8 to 14, characterized in that

the second sensor (104, 402, 504, 604) is recalibrated after a predetermined time interval after the startup of the system.