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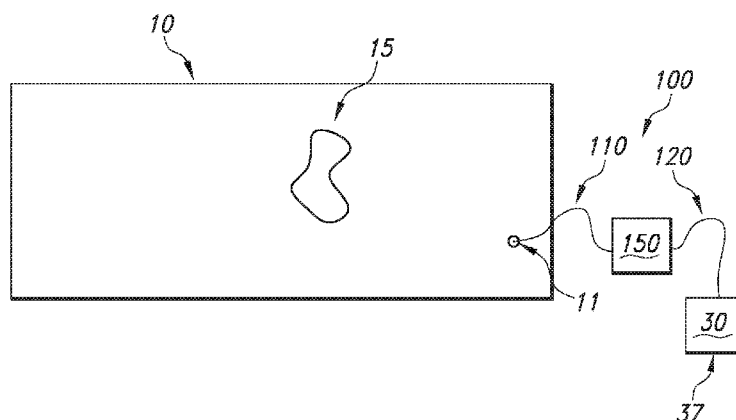


FIG. 1A

(57) Abstract: The invention provides a method for monitoring corrosion in a structure (10), the method comprising: monitoring voltage variations in the structure (10) with respect to a charge buffer (30) with an electrometer (150) functionally coupled with the structure (10) and with the charge buffer (30), and providing a related signal; and determining whether a corrosion event (15) takes place in dependence on the related signal.



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Corrosion measurement

FIELD OF THE INVENTION

5 The invention relates to a method for corrosion monitoring. The invention further relates to a sensor system for corrosion monitoring. The invention further relates to a use of an electrometer for corrosion monitoring.

BACKGROUND OF THE INVENTION

10 Methods for corrosion monitoring are known in the art. For instance, US6077418 describes monitoring corrosion of a metal member under heat transfer condition by using a test coupon made of the same material as that of the metal member. The test coupon may have a welded portion and a crevice. One substantial surface of the test coupon is heated by a sheet shaped heating element, and at least one portion of the other surface of the test coupon is
15 contacted with the corrosive fluid. After detecting a status of corrosion of the test coupon, the corrosion of the metal member is monitored based on the results of the detection. In case a counter electrode or reference electrode is used, the electrode is immersed in the corrosive fluid, and electrical signals between the test coupon and the electrode are measured. Then, the corrosion of the metal member is monitored.

20 JPH04270957A describes a method for measuring a degree of corrosion of a metal thin film which is coated on a surface of a synthetic rein molded object, the metal thin film is used as a test electrode and an electrode potential of the test electrode for a reference potential of a reference electrode is measured within an electrolyte.

WO9942811A1 describes a method and apparatus for the identification of
25 corrosion in a metal object. The method comprises analysing the statistical distribution of signals generated between two electrodes, typically exposed to the same corrosion conditions as the metal object, and preferably analyses the skewness and kurtosis of the signals.

US6015484A describes apparatus and methods for monitoring localized or pitting corrosion of metal or other material. A probe having a working electrode made of the same
30 material as the material being monitored is located in the same corroding environment as the material being monitored. The electrochemical noise detected between the working electrode and other electrodes is processed to provide an indication of the state of localized corrosion of the material being monitored. An anodic bias voltage is applied to the working electrode. This bias voltage accentuates localized corrosion at the working electrode.

EP0070124A2 describes a method of detecting and quantifying the occurrence of damage in ferrous metal structures comprising the steps of providing an electrolytic cell wherein, as one electrode, the metal structure to be monitored and at least one reference electrode are at least partially immersed in an electrolyte having properties which cause passivation of the immersed surface of the metal structure and at least a partial depassivation thereof when a flow of current to the passivated surface is established, for example by exposure of non-passivated surface in the event of surface damage, strain or crack, and once said surface has become initially passivated, detecting any change in the electro-chemical potential of the immersed metal structure, such change, according to its degree, enabling the damage to be detected and quantified.

10 The electrolyte is preferably sodium nitrite, the reference electrode is preferably of the same material as the metal structure, and the electro-chemical potential is measured by a high impedance volt meter connected between the metal structure and the reference electrode.

SUMMARY OF THE INVENTION

15 Corrosion is a highly dynamic process of material degradation that exists in various different forms and that may emerge unexpectedly at multiple different locations. Corrosion monitoring may be critical for safe operation of structures such as ships, aircrafts, vehicles, infrastructure and buildings. The prior art may describe corrosion monitoring using e.g. corrosion coupons, ultrasonic technique, (fiber-)optics, magnetism, eddy current or even local electrochemistry. In particular, prior art sensors may be classified in four categories: (i) direct sensors may measure the corrosion process directly at the structure, at the location of the sensor (e.g. based on electrochemistry); (ii) indirect sensors may measure the corrosion process indirectly on coupons that are assumed to be representative (e.g., based on electrochemistry or visual inspection); (iii) damage sensors may measure the corrosion damage instead of the actual corrosion process at the structure (e.g. based on (fiber-)optics, acoustics, magnetism or eddy current); and (iv) atmospheric sensors may measure potential corrosive conditions, *i.e.*, the sensor data may indicate whether corrosion has potentially occurred and may serve as an indirect corrosion indicator. However, all prior art methods may suffer from one or more drawbacks:

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The prior art methods may be restricted to locally detecting corrosion or corrosion damage *in situ* at an a-priori selected location. Hence, the prior art methods may provide corrosion monitoring on a small area. In particular, the methods may be incapable of detecting corrosion in challenging and severe operating conditions, such as in a high temperature environment, as the sensor may not last. Similarly, the methods may be incapable of detecting corrosion in inaccessible locations.

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The prior art methods may be incapable of distinguishing between different corrosion types.

The prior art methods may measure corrosion damage rather than the corrosion process, which may inevitably provide a delay in detection, and may complicate root-cause analyses, and may thereby impede preventing future corrosion events.

The prior art methods may rely on measuring a remote location that is only assumed to be representative. Further, typically, such methods do not account for all relevant parameters, such as the existence of welds, crevices, or the specific geometries of the structure.

The prior art methods may be maintenance-intensive as they may rely on, for example, electrolyte or coupon replacement, sometimes at hard-to-reach locations. This can be problematic as accessibility may be an important issue for the selection of a proper sensor location for prior art methods relying on electrolyte or coupon placement. The resulting sensor (and hence measurement) location is then potentially a compromise between the desired measurement location and the required sensor accessibility.

The (direct) sensors may be active and hence may accelerate or alter the corrosion mechanism at the sensor location.

Further, permanent sensor placement, either for direct corrosion or damage monitoring, either at the surface or embedded into the structure can also be considered as intrusive and may influence long-term measurement reliability, such as local coating behavior.

Further, in practice, corrosion sensors may typically only be allowed if these do not interfere with the system under investigation, which may not be the case for direct sensors as these typically generate a signal to measure corrosion and hence can be regarded as active instead of passive sensors.

Hence, it is an aspect of the invention to provide an alternative corrosion monitoring method and/or sensor system, which preferably further at least partly obviate one or more of above-described drawbacks. The present invention may have as object to overcome or ameliorate at least one of the disadvantages of the prior art, or to provide a useful alternative.

Hence, in a first aspect, the invention provides a method for monitoring corrosion in a structure. The method may comprise functionally, especially electrically, coupling an electrometer with the structure, especially at a first location. The method may further comprise functionally, especially electrically, coupling the electrometer with a charge buffer. The method may further comprise monitoring, especially detecting, voltage variations in the structure with respect to the charge buffer (using the electrometer) and providing a related signal, especially a raw related signal, and/or especially a processed related signal. In embodiments, the method may further comprise determining whether a corrosion event takes place in dependence on (an analysis

of) the related signal. Hence, especially the invention provides in embodiments a method for monitoring corrosion in a structure, the method comprising: (a) monitoring voltage variations in the structure with respect to a charge buffer with an electrometer functionally coupled with the structure and with the charge buffer, and providing a related signal; and (b) determining whether a corrosion event takes place in dependence on the related signal. Further, in embodiments the invention provides a method for monitoring corrosion in a structure, wherein the method comprises: (a) functionally coupling an electrometer with the structure; (b) functionally coupling the electrometer with a charge buffer; (c) monitoring voltage variations in the structure with respect to the charge buffer and providing a related signal; and (d) determining whether a corrosion event takes place in dependence on the related signal.

The method of the invention may provide the benefit that even with a single connection to a structure, large areas of the structure may be monitored for corrosion as it takes place. The method may further facilitate identifying the location of a corrosion event as well as of the corrosion type. In particular, the method may relate to measuring voltage variations, rather than absolute voltage values, as voltage variations may be indicative of an occurrence of a corrosion event.

In particular, the method may facilitate one or more of: (1) monitoring large areas at once; (2) monitoring from any location of the structure, (3); detecting a relatively small corrosion event, even at a remote location (of the first location); (4) identifying the corrosion type (of the corrosion event); (5) quantifying the severity of the corrosion event; (6) providing representative data, as the structure is monitored directly; (7) monitoring independent of an electrolyte at or near the first location; (8) long-term monitoring as little maintenance may be required; (9) passive sensing, i.e., the method essentially does not influence corrosion; and (10) providing a sensor system with essentially no interference with other systems, as the sensor system may be static, may essentially not emit energy, and may be configured to operate using energy spontaneously emitted by a corrosion event. Further, the method may be particularly suitable to measure a localized corrosion event. Hence, the method may facilitate monitoring of the most dangerous forms of corrosion: those that are essentially localized, hard to predict and detect and can lead to rapid functional failure.

Hence, the invention provides a method for monitoring corrosion in a structure.

The term “corrosion” may herein refer to the (undesired) chemical and/or electrochemical reactions of a material with its environment. In general the material, especially a metal, may be detrimentally affected by the corrosion, i.e., material properties of the material such as strength, appearance, and fluid permeability may be negatively affected by corrosion. The term “corrosion” may herein especially refer to one or more corrosion types selected from

the group comprising general corrosion, pitting corrosion, crevice corrosion, microbiologically influenced corrosion, weld decay and knifeline attack, environmentally induced cracking, hydrogen grooving, intergranular corrosion, stress corrosion cracking, dealloying and dezincification, erosion-corrosion, high-temperature corrosion and galvanic corrosion. The term “localized corrosion” may herein especially refer to one or more corrosion types selected from the group comprising pitting corrosion, crevice corrosion, microbiologically influenced corrosion, weld decay and knifeline attack, environmentally induced cracking, hydrogen grooving, intergranular corrosion, stress corrosion cracking, dealloying and dezincification, erosion-corrosion, high-temperature corrosion and galvanic corrosion (in case the attack is localized). Hence, “localized corrosion” is essentially non-general corrosion.

The term “general corrosion” may specifically refer to a corrosion type that takes place at almost the same rate on the surface of the entire material that is exposed to the corrosion-causing conditions. General corrosion may also be colloquially referred to as “uniform corrosion”, despite the corrosion generally not being truly uniform.

The term “structure” may herein refer to a physical object that may undergo corrosion. For example, the structure may be a piece of metal, a building, an infrastructure element, or a vehicle. The structure may especially comprise a (corrosion-sensitive) material, especially a material selected from the group comprising metals, metal-comprising composites, such as glass reinforced aluminum (“Glare”), and (corrosion-sensitive) polymers. In embodiments, the material may be electrically conductive.

In embodiments, the structure may have a floating voltage, such as, for example, an aircraft (during use). The method may be particularly suitable for corrosion monitoring of ungrounded structures.

The term “corrosion-sensitive” herein refers to the property of having the potential to corrode, not necessarily to a property of corroding easily or quickly.

The method may comprise functionally coupling, especially electrically coupling, an electrometer with the structure, especially at a first location. In embodiments, the method may comprise connecting the electrometer with the structure via a first electrical connection, especially at a first location.

The term “electrometer” may herein especially refer to an instrument for measuring an electrical voltage difference between two sources, such as between the structure and the charge buffer. In particular, the electrometer may be configured to essentially not “leak” current as it measures the electrical voltage difference, *i.e.*, the electrometer may have a high impedance. In embodiments, the electrometer may comprise a device configured to measure an electrical voltage difference between two sources. In further embodiments, the electrometer may

comprise a device selected from the group comprising a (high-impedance) voltmeter, and a potentiostat.

The method may further comprise functionally coupling, especially electrically coupling, the electrometer with a charge buffer. In embodiments, the method may comprise
5 connecting the electrometer with the charge buffer via a second electrical connection.

The term “charge buffer” may herein refer to a reference element with a (relatively) stable charge, especially with respect to a measurement duration. The charge buffer may, for example, have a stable charge for time periods of at least 100 s, such as of at least 1000s. The charge buffer may especially be a floating reference. In embodiments, the charge buffer may,
10 for example, be a grounded connection (i.e. a physical connection to the ground), or a reference electrode.

Hence, the electrometer may be functionally coupled to both the structure and the charge buffer, and may (be configured to) measure voltage variations in the structure with respect to the charge buffer.

Specifically, in embodiments, the method may comprise monitoring, especially
15 detecting, (time-dependent) voltage variations in the structure with respect to the charge buffer (using the electrometer) and providing a related signal, especially a raw related signal, and/or especially a processed related signal. The related signal may especially comprise (raw and/or processed) information pertaining to (presence and/or absence of) the voltage variations. Hence,
20 if no voltage variations occurred, especially with regards to a time period, the related signal may indicate that no voltage variations were detected (during the time period). The related signal may especially comprise data related to the voltage difference between the structure and the charge buffer over time.

In further embodiments, the method may comprise determining whether a
25 corrosion event takes place (in the structure) in dependence on the related signal, especially based on a (computational) analysis of the related signal. In particular, a gradual change in the voltage variations (also “drift”) may indicate a general corrosion event. Further, a voltage transient (or: “transient voltage variation”) may indicate a localized corrosion event.

The term “voltage transient” may herein especially refer to a finite signal feature,
30 otherwise described as a sudden change in the voltage signal, superimposed on the mean value, which is in steady-state or may be drifting on a larger timescale. In particular, when plotted, a voltage transient may resemble a (small) peak relative to a steady state or to a gradually changing voltage signal. The voltage transient may be particularly informative with regards to a localized corrosion event, and particularly with respect to the kinetics of the corrosion event.

The term “corrosion event” may herein especially refer to an occurrence of corrosion. The corrosion event may especially be a general corrosion event, or may especially be a localized corrosion event. The term “corrosion event” may also refer to a plurality of corrosion events, especially a plurality of sequentially occurring corrosion events, or especially a plurality of simultaneously occurring corrosion events. Simultaneously occurring corrosion events may each have their own characteristic kinetics, and may hence be distinguished and identified using the method of the invention.

In specific embodiments, the method comprises: functionally coupling an electrometer with the structure; functionally coupling the electrometer with a charge buffer; monitoring voltage variations in the structure with respect to the charge buffer and providing a related signal; and determining whether a corrosion event takes place in dependence on the related signal.

It will be clear to the person skilled to the art that the invention relates to a method for monitoring corrosion. Hence, the method is not restricted to concurrence with a corrosion event.

The detection of localized corrosion may be particularly important. For example, a vehicle, such as an aircraft, may appear to be in an excellent condition, whereas the structure may be substantially weakened, especially dangerously weakened, due to localized corrosion. However, given the local nature of such corrosion, localized corrosion may be difficult to predict and may have been particularly difficult to detect with prior art methods.

In embodiments, the method may comprise monitoring a voltage transient in the structure with respect to the charge buffer and providing a related signal, *i.e.*, the related signal may comprise information related to the (absence and/or presence of) a voltage transient. In further embodiments, the method may comprise determining whether a localized corrosion event takes place in dependence on the related signal.

Hence, in embodiments, the voltage variations may comprise a voltage transient, and the corrosion event may be a localized corrosion event. In further embodiments, the method may comprise monitoring a voltage transient, especially relative to a drift and/or relative to a steady state, especially relative to a steady state, and determining whether a localized corrosion event takes place based on the voltage transient.

In further embodiments, the method may comprise, when detecting drift in the structure and/or the charge buffer, to wait for steady state conditions.

In embodiments, the method may comprise subtracting a DC-component (direct current) from the detected voltage variation. In particular, the method may comprise subtracting the DC-component from a measured signal after measuring the first data point(s), *i.e.*, the first

data point(s) may be used as a fixed offset. Hence, the subtraction of the DC-component may provide the benefit that a higher resolution may be made available within the relevant measurement range. For example, without subtracting the DC-component, an electrometer may provide a 24-bit measurement spread out over a measurement range of several volts, whereas the relevant range for a voltage transient may be in the order of 1 – 100 mV.

Besides detection of the occurrence of corrosion, it may further be beneficial to detect the corrosion type. The term “corrosion type” may herein refer to the corrosion of different metals, such as a corrosion type selected from the group comprising aluminum corrosion, steel corrosion, or corrosion of other alloys, and may refer to a corrosion type selected from the group comprising general corrosion, pitting corrosion, crevice corrosion, environmentally induced cracking, hydrogen damage, intergranular corrosion, stress corrosion cracking, dealloying and dezincification, erosion-corrosion, high-temperature corrosion, and galvanic corrosion, especially from the group comprising pitting corrosion, crevice corrosion, environmentally induced cracking, hydrogen damage, intergranular corrosion, stress corrosion cracking, dealloying and dezincification, erosion-corrosion, high-temperature corrosion, and galvanic corrosion (in case of localized attack). Determining the corrosion type may be both informative regarding the corrosion location, as well as regarding the appropriate follow-up action.

Hence, in embodiments, when a corrosion event is detected, the method may comprise identifying a corrosion type of the corrosion event, especially based on the detected voltage transient, more especially based on the kinetics of the voltage transient, or such as based on a time-frequency analysis, especially based on a wavelet decomposition of the voltage transient, or especially based on a Hilbert-Huang spectrum.

Further, it may be beneficial to detect the corrosion location.

In embodiments, the method may comprise functionally coupling the electrometer with the structure at a first location, wherein the method further comprises estimating a distance between the first location and a localized corrosion event in the structure, especially based on the amplitude of the voltage transient. In particular, there may be some (minor) loss between the location of the corrosion event and the first location. Hence, by measuring at multiple (first) locations, the location of the corrosion event may be pinpointed, for example via triangulation (also “via a triangle survey”). For example, in embodiments, the method may comprise a triangular measurement with three (or more) first locations measured simultaneously. In such embodiments, the amplitude difference between the measurements of the same voltage transient may be indicative of the location of the corrosion event.

Hence, in further embodiments, the method may comprise functionally coupling a plurality of electrometers, especially three or more electrometers, with the structure at a plurality

of locations and with the (single) charge buffer, especially with a plurality of charge buffers. In further embodiments, the method may comprise locating the corrosion event in the structure based on the voltage variations.

As will be clear to the person skilled in the art, as the amplitude differences may
5 be minor, the plurality of electrometers may – in view of their voltage resolution – need to be spaced appropriately. For example, in embodiments, the plurality of electrometers may be functionally coupled with the structure at a plurality of locations, wherein the (average) distance between each of the locations of the plurality of locations is at least 1 m.

In further embodiments, the structure may be selected from the group comprising
10 an infrastructure element, such as a bridge or a power grid element, a vehicle, such as an aircraft, a ship, a submarine, a spacecraft, and a car, or a building.

Preferably, there is essentially no current between the structure and the charge buffer (via the electrometer), especially as any current flow may nullify the voltage difference. Hence, in embodiments, the electrometer may have an input impedance (i.e. impedance between
15 the two electrometer connectors) of at least 10^{10} Ohm, such as at least 10^{11} Ohm, especially at least 10^{12} Ohm.

In embodiments, the charge buffer may be a floating reference.

In further embodiments, the charge buffer may comprise a reference electrode, especially an internal reference electrode, *i.e.*, a sensor system may comprise both the (internal)
20 reference electrode and the electrometer. Such embodiments may be particularly beneficial in settings where no grounding is available.

In further embodiments, the charge buffer may comprise a grounded connection. The grounded connection may be particularly suitable to act as a charge buffer and may essentially generate no (effective) drift.

25 In further embodiments, the charge buffer may comprise a grounded connection. A benefit of measuring against a grounded connection may be that there may be (relatively) little drift. However, other electrical appliances connected to the grounded connection may provide interference. Hence, in further embodiments, the method may comprise a parallel measurement, *i.e.*, the method may further comprise functionally coupling a second electrometer to the
30 grounded connection and to a (second) (internal) reference electrode. Thereby, the method may account for the interference of other electrical appliances connected to the grounded connection.

In embodiments, the method may comprise executing a computational analysis of the related signal, especially with an algorithm, or especially with artificial intelligence, to determine whether a corrosion event takes place.

In further embodiment, the computational analysis may comprise determining whether a corrosion event takes place, especially by comparing the related signal to corrosion-related data in an (off-/online or internet) database.

In further embodiments, when a corrosion event is detected, the computational
5 analysis may comprise comparing the related signal to corrosion-related data in a database, wherein the database comprises corrosion-related data for different corrosion types, and wherein the computational analysis comprises identifying the corrosion type of the corrosion event. In further embodiments, the computational analysis may comprise comparing the related signal to corrosion-related data in the database based on the structure, such as based on materials present
10 in the structure, which may facilitate a more targeted and/or quicker analysis.

In further embodiments, the method may comprise using an artificial intelligence trained (i) to distinguish between drift and a voltage transient in dependence on the related signal, and/or (ii) to determine whether a corrosion event takes place, and/or (iii) to identify the corrosion type.

15 In a second aspect, the invention may provide a sensor system for corrosion monitoring. The sensor system may comprise an electrometer, a first electrical connection, and a second electrical connection. Especially, the first electrical connection and the second electrical connection may be functionally coupled, especially electrically coupled, to the electrometer. In embodiments, the first electrical connection may be configured for functional coupling to a
20 structure, especially at a first location (of the structure). In further embodiments, the second electrical connection may be configured for functional coupling to a charge buffer. In further embodiments, the electrometer may have an input impedance of at least 10^{10} Ohm, especially 10^{11} Ohm, such as 10^{12} Ohm.

Hence, the invention may provide a sensor system for corrosion monitoring in a
25 structure. It will be clear to the person skilled in the art that the structure is, generally, not part of the sensor system. Rather, the sensor system is configured to monitor corrosion at the structure.

In embodiments, the sensor system may be a sensor device.

In embodiments, the sensor system may comprise an (internal) reference electrode, wherein the (internal) reference electrode is the charge buffer, and wherein the second electrical
30 connection is functionally coupled to the (internal) reference electrode.

In further embodiments, the internal reference electrode may comprise an Ag-based electrode, especially an AgCl-based electrode.

In further embodiments, the internal reference electrode may be arranged in an electrolyte, especially a (saturated) KCl solution.

During operation, the sensor system, especially the electrometer, may be functionally coupled to the structure via the first electrical connection.

In embodiments, the sensor system may further comprise a control system. In further embodiments, the sensor system may have an operational mode. In the operational mode
5 (of the sensor system): the electrometer may (be configured to) detect (time-dependent) voltage variations in the structure with respect to the charge buffer and may (be configured to) provide a (raw and/or processed) related signal, especially to the control system. Further, in embodiments, in the operational mode, the control system may (be configured to) determine whether a corrosion event takes place in dependence on the related signal.

10 In further embodiments, in the operational mode, the electrometer may (be configured to) detect a voltage transient in the structure with respect to the charge buffer and provide the related signal. In further embodiments, in the operational mode, the control system may (be configured to) determine whether a localized corrosion event takes place (in the structure) in dependence on the related signal, and, when a localized corrosion event is detected,
15 the control system may (be configured to) identify the corrosion type of the corrosion event based on the related signal, especially based on information in the related signal pertaining to the voltage transient.

In embodiments, the sensor system may especially be configured to execute the method of the invention. In particular, the control system may be configured to (have the sensor
20 system) execute the method of the invention.

In embodiments, the sensor system may comprise a plurality of electrometers, a plurality of first connection elements, and a plurality of second connection elements. In particular, each of the plurality of electrometers may be functionally coupled to a respective first connection element and a respective second connection element. Such embodiment may be particularly
25 beneficial when measuring at a plurality of (first) locations, especially in order for localization of corrosion events, or when using the ground as charge buffer, and simultaneously measuring a reference electrode with respect to ground.

As indicated above, in embodiments, the first electrical connection may be configured for functional coupling at a first location (of the structure). The sensor system,
30 especially the control system, may, in such embodiments, be configured to estimate (or “determine”) a distance between the first location and a localized corrosion event, especially based on the voltage variations.

In particular, in embodiments, the operational mode may comprise the control system estimating a distance between the first location and a localized corrosion event in the
35 structure, especially based on the amplitude of a voltage transient. In particular, there may be

some (minor) loss between the location of the corrosion event and the first location. Hence, by measuring at multiple (first) locations, the location of the corrosion event may be pinpointed, for example via triangulation (also “via a triangle survey”). For example, in embodiments wherein the sensor system comprises a plurality of electrometers and a plurality of first connection
5 elements, the operational mode may comprise a triangular measurement with three (or more) first locations measured simultaneously. In such embodiments, the amplitude difference between the measurements of the same voltage transient may be indicative of the location of the (localized) corrosion event.

Hence, in embodiments, the sensor system may be configured for providing
10 functional coupling of a plurality of electrometers with the structure and the charge buffer, and the operational mode may comprise the control system locating a (localized) corrosion event in the structure based on the voltage variations.

In further embodiments, the sensor system may comprise a wireless communication unit, especially a radio-frequency identification tag. The wireless communication
15 unit may be configured to enable communication between the electrometer and the (remotely arranged) control system. The wireless communication unit may further be configured to communicate with a second system, such as a notification system, or such as an alarm system. In particular, the wireless communication unit may facilitate corrosion monitoring at hard-to-access and/or remote locations.

20 In further embodiments, the sensor system may be integrated in a single device, *i.e.*, the sensor system may be a single physically connected device.

In further embodiments, the sensor system may comprise a housing, especially wherein the housing encloses the charge buffer and the electrometer (functionally coupled with the structure and with the charge buffer).

25 In further embodiments, the sensor system may comprise a first electrical connection (or “first electrical connector”) functionally coupled to the electrometer and configured to be functionally coupled with the structure, especially wherein (at least part of) the first electrical connection is movable relative to the housing.

In further embodiments, the sensor system may comprise a second electrical
30 connection (or “second electrical connector”) functionally coupled to the electrometer and configured to be functionally coupled with the charge buffer, especially wherein (at least part of) the second electrical connection is movable relative to the housing.

The sensor system, especially the control system, may have an operational mode. The term “operational mode” may also be indicated as “controlling mode”. The sensor system,
35 or apparatus, or device may execute an action in a “mode” or “operational mode” or “mode of

operation". Likewise, in a method an action, stage, or step may be executed in a "mode" or "operation mode" or "mode of operation". This does not exclude that the system, or apparatus, or device may also be adapted for providing another operational mode, or a plurality of other operational modes. Likewise, this does not exclude that before executing the mode and/or after
5 executing the mode one or more other modes may be executed. However, in embodiments a control system may be available, that is adapted to provide at least the operational mode. Would other modes be available, the choice of such modes may especially be executed via a user interface, though other options, like executing a mode in dependence of a sensor signal or a (time) scheme, may also be possible. The operational mode may in embodiments also refer to a system,
10 or apparatus, or device, that can only operate in a single operation mode (i.e. "on", without further tunability).

The term "controlling" and similar terms herein may especially refer at least to determining the behavior or supervising the running of an element. Hence, herein "controlling" and similar terms may e.g. refer to imposing behavior to the element (determining the behavior
15 or supervising the running of an element), etc., such as e.g. measuring, displaying, actuating, opening, shifting, changing temperature, etc.. Beyond that, the term "controlling" and similar terms may additionally include monitoring. Hence, the term "controlling" and similar terms may include imposing behavior on an element and also imposing behavior on an element and monitoring the element. The controlling of the element can be done with a control system. The
20 control system and the element may thus at least temporarily, or permanently, functionally be coupled. The element may comprise the control system. In embodiments, the control system and the element may not be physically coupled. Control can be done via wired and/or wireless control. The term "control system" may also refer to a plurality of different control systems, which especially are functionally coupled, and of which e.g. one control system may be a control system
25 and one or more others may be slave control systems.

In a further aspect, the invention may provide a use of an electrometer for monitoring corrosion in a structure, wherein the use comprises detecting (or "monitoring for") voltage variations, especially a voltage transient, in the structure with respect to a charge buffer.

In a further aspect, the invention may provide a use of the sensor system according
30 to the invention for corrosion monitoring.

In a further aspect, the invention may provide a use of remote monitoring of a voltage transient in a structure (through a single connection) to identify localized corrosion events in the structure.

The embodiments described herein are not limited to a single aspect of the
35 invention. For example, an embodiment describing the method may, for example, further relate

to the sensor system, especially to the operational mode, or especially to the control system. Similarly, an embodiment of the sensor system describing an electrolyte may further relate to embodiments of the method involving the internal reference electrode. In particular, an embodiment of the method describing an operation (of the sensor system) may indicate that the sensor system may, in embodiments, be configured for and/or be suitable for the operation.

The invention may be applied for monitoring of structures such as infrastructure, buildings, and vehicles. The invention may further also be applied in labs, for example for corrosion research. The invention may further also enable, especially be applied to, replace expensive, and/or rare (relatively) and/or toxic corrosion-proof materials, such as a Chrome(VI)-material, with cheaper, more abundant and/or less toxic materials, as an efficient and flexible monitoring method may compensate for some less preferable material properties, like in the case of the replacement of toxic corrosion inhibitors, such as a Chrome(VI)-material, with other, potentially less effective, corrosion inhibitors.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings in which corresponding reference symbols indicate corresponding parts, and in which: Fig. 1A-B schematically depict embodiments of the method and the sensor system of the invention. Fig. 2A-D schematically depict experimental observations of corrosion of an AA2024-T3 (UNS A92024) alloy obtained with a comparative example and with the method of the invention. Fig. 3A-B schematically depict experimental observations of corrosion of stainless steel AISI304 (UNS S30400) obtained with the method of the invention. The schematic drawings are not necessarily on scale.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Fig. 1A schematically depicts an embodiment of the method for monitoring corrosion in a structure 10. In the depicted embodiment, the structure 10 may comprise a (corrosion-sensitive) material that is electrically conductive, especially a material selected from the group comprising metals, metal-comprising composites, such as glass reinforced aluminum (“Glare”), and (corrosion-sensitive) polymers. In the depicted embodiment, the structure may especially comprise a metal plate. The method may comprise functionally coupling an electrometer 150 with the structure 10. The method may further comprise coupling the electrometer 150 with a charge buffer 30. In the depicted embodiment, the charge buffer 30 comprises a grounded connection 37. The method may further comprise monitoring voltage

variations in the structure 10 with respect to the charge buffer 30 and providing a related signal; and determining whether a (localized) corrosion event 15 takes place in dependence on the related signal.

The depicted embodiment may, for example, relate to monitoring of corrosion
5 under thin-film or (extremely) low-volume electrolyte in a lab setting, such as atmospheric corrosion, such as in the context of coating research and/or for research related to the efficacy of corrosion inhibitors, especially such as Cr(VI) alternatives.

In embodiments, the method may comprise functionally coupling the electrometer
150 with the structure 10 at a first location 11, wherein the method comprises estimating a
10 distance between the first location 11 and a corrosion event 15 in the structure 10 based on the voltage variations.

In further embodiments, the method may comprise executing a computational analysis of the related signal to determine whether a corrosion event 15 takes place.

Fig. 1A further schematically depicts an embodiment of the sensor system 100 for
15 corrosion monitoring. The sensor system 100 comprising an electrometer 150, a first electrical connection 110, and a second electrical connection 120, wherein the first electrical connection 110 and the second electrical connection 120 are functionally coupled to the electrometer 150, and wherein the first electrical connection 110 is configured for functional coupling to a structure 10, and wherein the second electrical connection 120 is configured for functional coupling to a
20 charge buffer 30, here especially the (internal) reference electrode 130, and wherein the electrometer 150 has an input impedance of at least 10^{10} Ohm, such as at least 10^{11} Ohm, especially at least 10^{12} Ohm.

In the depicted embodiment, the sensor system 100 comprises a housing, wherein the housing encloses the electrometer 150. Further, in the depicted embodiment, (at least part of)
25 the first electrical connection 110 is (configured to be) movable relative to the housing. Similarly, (at least part of) the second electrical connection 120 is (configured to be) movable relative to the housing.

Fig. 1A further schematically depicts a use of an electrometer 150 for monitoring corrosion in a structure 10, wherein the use comprises detecting voltage variations in the structure
30 10 with respect to a charge buffer 30.

Fig. 1B schematically depicts another embodiment of the method for corrosion monitoring. In the depicted embodiment, the structure 10 comprises a vehicle, especially an aircraft. Further, in the depicted embodiment, the electrometer 150 is functionally coupled to a charge buffer 30, wherein the charge buffer 30 is a reference electrode 130, especially an internal

reference electrode *i.e.*, internal to the sensor system 100, especially internal to the electrometer 150.

In the depicted embodiment, the method comprises functionally coupling a plurality of electrometers 150 with the structure 10, especially at a plurality of first locations 5 11, 11a, 11b, 11c, and the charge buffer 30, especially with a plurality of (respective) charge buffers 30, especially wherein the method comprises locating the corrosion event 15 in the structure 10 based on the voltage variations, especially through triangulation.

Fig. 1B further schematically depicts an embodiment of the sensor system 100 for corrosion monitoring. In the depicted embodiment, the sensor system 100 comprises a reference 10 electrode 130, wherein the reference electrode 130 is the charge buffer 30, and wherein the second electrical connection 120 (for visualization purposes not depicted) is functionally coupled to the reference electrode 130.

In the depicted embodiment, the sensor system 100, especially the electrometer, may be integrated in the structure 10. In particular, in the depicted embodiment, the sensor 15 system 100 is integrated in a single device, wherein the single device is integrated in the structure 10. Further, the sensor system 100 may comprise a housing, wherein the housing encloses the charge buffer 30 and the electrometer 150. Further, the sensor system may comprise a first electrical connection 110 (not depicted) functionally coupled to the electrometer 150 and configured to be functionally coupled with the structure 10.

20 In the depicted embodiment, the sensor system 100 further comprises a control system 300.

In further embodiment, in an operational mode: the electrometer 150 may detect voltage variations 50 in the structure 10 with respect to the charge buffer 30 and provides a related signal; and the control system 300 may determine whether a corrosion event 15 takes place in 25 dependence on the related signal.

In further embodiments, the electrometer 150 may (be configured to) detect voltage transients 50 in the structure 10 with respect to the charge buffer 30 and provide the related signal. In further embodiments, the control system 300 may (be configured to) determine whether a localized corrosion event 15 takes place in dependence on the related signal, and 30 especially, when a localized corrosion event 15 is detected, the control system 300 may (be configured to) identify the corrosion type of the localized corrosion event 15 based on the related signal.

Experiments

The measurements were performed in a conventional two-electrode configuration 35 under open-circuit conditions, with a working electrode (either stainless steel: AISI304 (UNS

S30400), or an aluminum alloy: AA2024-T3 (UNS A92024)). The working electrodes were partly coated with an epoxy primer to prevent crevice corrosion and embedded in coupons using an epoxy resin. Only a well-defined area of 0.05 cm^2 of the working electrode was exposed in the electrolyte. The working electrodes were wet ground using up to 4000-grit SiC paper. The reference electrode used was a Radiometer analytical Red Rod type REF201 (Ag/AgCl/sat. KCl: 0.207 V vs. SHE (standard hydrogen electrode)). The electrolyte used was an aqueous 3 wt.% NaCl solution. All solutions were open to air. The electrochemical cells were placed in a Faradaic cage to reduce, especially avoid, electromagnetic disturbance from external sources. The ambient temperature was controlled at 20 °C. Measurements were carried out multiple times. A low-pass filter of 10 Hz was applied during data recording. The data were processed using Matlab from MathWorks. The maximum range of the potentiometer was set at 100 mV. In order to maximize the resolution of the raw potential signal measurement (i.e. in order to limit the potential range), for each measurement the value of the first potential measurement was used as a fixed offset for the entire potential data range.

The electrometer used was a Compactstat from Ivium Technologies, controlled by a Windows-based PC running dedicated software.

Fig. 2A-D schematically depict experimental observations of corrosion of an aluminium alloy (AA2024-T3 (UNS A92024)) immersed in an NaCl. Specifically, Fig. 2A-B schematically depict experimental observations obtained with a prior art technique. This prior art technique, also called ‘electrochemical noise’, detects corrosion processes based on the current, measured between two identical working electrodes, and/or the open corrosion potential, measured between the two working electrodes and a laboratory reference electrode which is immersed in the same electrolyte as the working electrodes, as described in Homborg *et al.*, “*Novel time-frequency characterization of electrochemical noise data in corrosion studies using Hilbert spectra*”, Corrosion science, 66, 2013, pages 97-110, which is hereby herein incorporated by reference. In the present case, a single working electrode was exposed in the electrolyte, hence a potential signal (denoted as ‘electrochemical potential noise’ in the literature) was obtained. Fig. 2A therefore reflects the potential between a single working electrode and a laboratory reference electrode which is immersed in the same electrolyte as the working electrode. Fig. 2C-D schematically depict experimental observations obtained with the method of the invention. In particular, the measurements with the prior art method and the method of the invention were performed simultaneously on the same structure 10.

Fig. 2A, 2C schematically depict the observed voltage variations E (in volt) over time (in seconds). As can be seen, the method of the invention provides highly similar results as the prior art method. Specifically, the two signals primarily differ in the absolute value of the

voltage, depicted along the y-axis. The two plots may be considered translated as the transient information, including amplitudes, is comparable. The translation is limited in this case, due to the DC removal prior to the recording of the data points, in order to maximize the resolution within the voltage range. In particular, the same voltage transients 50 are captured in the experimental data. The limited differences that may be observed between the voltage transients may be due to each method being performed with a separate laboratory reference electrode. Hence, the method may comprise: detecting a voltage transient 50 in the structure 10 with respect to the charge buffer 30 using the electrometer 150 and providing the (raw) related signal; and especially determining whether a localized corrosion event 15 takes place in dependence on the related signal.

Fig. 2B, 2D schematically depict continuous wavelet decompositions of the experimental data of Fig. 2A, 2C, respectively. Specially, Fig. 2B, 2D depict the time-varying (x-axis, in seconds) energy distribution of each signal over the different timescales, translated into frequencies f (in Hz). Again, the method of the invention provides highly similar results as the prior art method. Hence, the method of the invention may provide essentially the same kinetic information as the prior art method, but with additional benefits, such as without necessitating monitoring directly at the surface, nor requiring immersed conditions.

Fig. 3A-B schematically depict experimental observations of corrosion of AISI304 [UNS S30400] obtained with the method of the invention. Specifically, Fig. 3A depicts the observed voltage variations E (in volt) over time (in seconds), and Fig. 3B schematically depicts a continuous wavelet decomposition of the experimental data of Fig. 3A.

Fig. 2C-D, and 3A-B further highlight that different corrosion types, such as localized corrosion in different materials, may provide distinct signals when observed with the method of the invention.

Hence, in embodiments, when a corrosion event 15 is detected, the method may comprise identifying a corrosion type of the corrosion event 150. The identification of the corrosion type of a corrosion event 15 based on a time-frequency analysis may be further described in Homborg *et al.*, “*Novel time-frequency characterization of electrochemical noise data in corrosion studies using Hilbert spectra*”, Corrosion science, 66, 2013, pages 97-110 and Homborg *et al.*, “*Wavelet Transform Modulus Maxima and Holder Exponents Combined with Transient Detection for the Differentiation of Pitting Corrosion Using Electrochemical Noise*”, Corrosion, 74, 2018, pages 1001-1010, which are hereby herein incorporated by reference.

Further, the experimental data indicate that the corrosion events 15 are in the frequency domain typically represented at frequencies < 1 Hz. Hence, in embodiments, the

method may comprise a time-frequency analysis wherein the corrosion events 15 are detected at frequencies ≤ 5 Hz, such as ≤ 2 Hz, especially ≤ 1 Hz, such as ≤ 0.5 Hz

The term “plurality” refers to two or more. Furthermore, the terms “a plurality of” and “a number of” may be used interchangeably.

5 The terms “substantially” or “essentially” herein, and similar terms, will be understood by the person skilled in the art. The terms “substantially” or “essentially” may also include embodiments with “entirely”, “completely”, “all”, etc. Hence, in embodiments the adjective substantially or essentially may also be removed. Where applicable, the term “substantially” or the term “essentially” may also relate to 90% or higher, such as 95% or higher,
10 especially 99% or higher, even more especially 99.5% or higher, including 100%. Moreover, the terms “about” and “approximately” may also relate to 90% or higher, such as 95% or higher, especially 99% or higher, even more especially 99.5% or higher, including 100%. For numerical values it is to be understood that the terms “substantially”, “essentially”, “about”, and “approximately” may also relate to the range of 90% - 110%, such as 95%-105%, especially 99%-
15 101% of the values(s) it refers to.

The term “comprise” includes also embodiments wherein the term “comprises” means “consists of”.

The term “and/or” especially relates to one or more of the items mentioned before and after “and/or”. For instance, a phrase “item 1 and/or item 2” and similar phrases may relate
20 to one or more of item 1 and item 2. The term “comprising” may in an embodiment refer to “consisting of” but may in another embodiment also refer to “containing at least the defined species and optionally one or more other species”.

Furthermore, the terms first, second, third and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a
25 sequential or chronological order. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments of the invention described herein are capable of operation in other sequences than described or illustrated herein.

The devices, apparatus, or systems may herein amongst others be described during operation. As will be clear to the person skilled in the art, the invention is not limited to methods
30 of operation, or devices, apparatus, or systems in operation.

The term “further embodiment” and similar terms may refer to an embodiment comprising the features of the previously discussed embodiment, but may also refer to an alternative embodiment.

It should be noted that the above-mentioned embodiments illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative embodiments without departing from the scope of the appended claims.

In the claims, any reference signs placed between parentheses shall not be
5 construed as limiting the claim.

Use of the verb "to comprise" and its conjugations does not exclude the presence of elements or steps other than those stated in a claim. Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise", "comprising", "include", "including", "contain", "containing" and the like are to be construed in an inclusive
10 sense as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to".

The article "a" or "an" preceding an element does not exclude the presence of a plurality of such elements.

The invention may be implemented by means of hardware comprising several
15 distinct elements, and by means of a suitably programmed computer. In a device claim, or an apparatus claim, or a system claim, enumerating several means, several of these means may be embodied by one and the same item of hardware. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

20 The invention also provides a control system that may control the device, apparatus, or system, or that may execute the herein described method or process. Yet further, the invention also provides a computer program product, when running on a computer which is functionally coupled to or comprised by the device, apparatus, or system, controls one or more controllable elements of such device, apparatus, or system.

25 The invention further applies to a device, apparatus, or system comprising one or more of the characterizing features described in the description and/or shown in the attached drawings. The invention further pertains to a method or process comprising one or more of the characterizing features described in the description and/or shown in the attached drawings. Moreover, if a method or an embodiment of the method is described being executed in a device,
30 apparatus, or system, it will be understood that the device, apparatus, or system is suitable for or configured for (executing) the method or the embodiment of the method respectively.

The various aspects discussed in this patent can be combined in order to provide additional advantages. Further, the person skilled in the art will understand that embodiments can be combined, and that also more than two embodiments can be combined. Furthermore, some of
35 the features can form the basis for one or more divisional applications.

CLAIMS:

- 5 1. A method for monitoring corrosion in a structure (10), the method comprising:
monitoring voltage variations in the structure (10) with respect to a charge buffer (30)
with an electrometer (150) functionally coupled with the structure (10) and with the
charge buffer (30), and providing a related signal; and
determining whether a corrosion event (15) takes place in dependence on the related
10 signal.
2. The method according to claim 1, wherein the method comprises:
detecting a voltage transient (50) in the structure (10) with respect to the charge buffer
(30) using the electrometer (150) and providing the related signal; and
15 determining whether a localized corrosion event (15) takes place in dependence on the
related signal.
3. The method according to any one of the preceding claims, wherein when the
corrosion event (15) is detected, the method comprises identifying a corrosion type of the
20 corrosion event (15).
4. The method according to any one of the preceding claims, wherein the method
comprises functionally coupling the electrometer (150) with the structure (10) at a first location
(11), wherein the method comprises estimating a distance between the first location (11) and a
25 corrosion event (15) in the structure (10) based on the voltage variations.
5. The method according to claim 4, wherein the method comprises functionally
coupling a plurality of electrometers (150) with the structure (10) and the charge buffer (30), and
wherein the method comprises locating the corrosion event (15) in the structure (10) based on the
30 voltage variations.
6. The method according to any one of the preceding claims, wherein the structure
(10) is selected from the group comprising an infrastructure element and a vehicle.

7. The method according to any one of the preceding claims, wherein the electrometer (150) has an input impedance of at least 10^{11} Ohm.
8. The method according to any one of the preceding claims, wherein the charge
5 buffer (30) comprises a reference electrode (130).
9. The method according to any one of the preceding claims 1 – 7, wherein the charge buffer (30) comprises a grounded connection (37).
- 10 10. The method according to any one of the preceding claims, wherein the method comprises executing a computational analysis of the related signal to determine whether a corrosion event (15) takes place.
11. A sensor system (100) for corrosion monitoring, the sensor system (100)
15 comprising an electrometer (150), a first electrical connection (110), and a second electrical connection (120), wherein the first electrical connection (110) and the second electrical connection (120) are functionally coupled to the electrometer (150), and wherein the first electrical connection (110) is configured for functional coupling to a structure (10), and wherein the second electrical connection (120) is configured for functional coupling to a charge buffer
20 (30), and wherein the electrometer (150) has an input impedance of at least 10^{11} Ohm, wherein the sensor system (100) further comprises a control system (300), and wherein in an operational mode:
the electrometer (150) is configured to detect voltage variations (50) in the structure (10) with respect to the charge buffer (30) and to provide a related signal; and
25 the control system (300) is configured to determine whether a corrosion event (15) takes place in dependence on the related signal.
12. The sensor system (100) according to claim 11, wherein the sensor system (100) comprises a reference electrode (130) wherein the second electrical connection (120) is
30 functionally coupled to the reference electrode (130), and wherein the reference electrode (130) is the charge buffer (30).

13. The sensor system (100) according to any one of the preceding claims 11-12, wherein in the operational mode:

the electrometer (150) is configured to detect voltage transients (50) in the structure (10) with respect to the charge buffer (30) and provides the related signal;

5 the control system (300) is configured to determine whether a localized corrosion event (15) takes place in dependence on the related signal, and, when a localized corrosion event (15) is detected, the control system (300) is configured to identify the corrosion type of the localized corrosion event (15) based on the related signal.

10 14. The sensor system (100) according to any one of the preceding claims 11-13, wherein the sensor system (100) is integrated in a single device, wherein the sensor system comprises a housing, wherein the housing encloses the charge buffer (30) and the electrometer (150), and wherein at least part of the first electrical connection (110) is movable relative to the housing.

15

15. Use of an electrometer (150) for monitoring corrosion in a structure (10), wherein the use comprises detecting voltage variations in the structure (10) with respect to a charge buffer (30).

20

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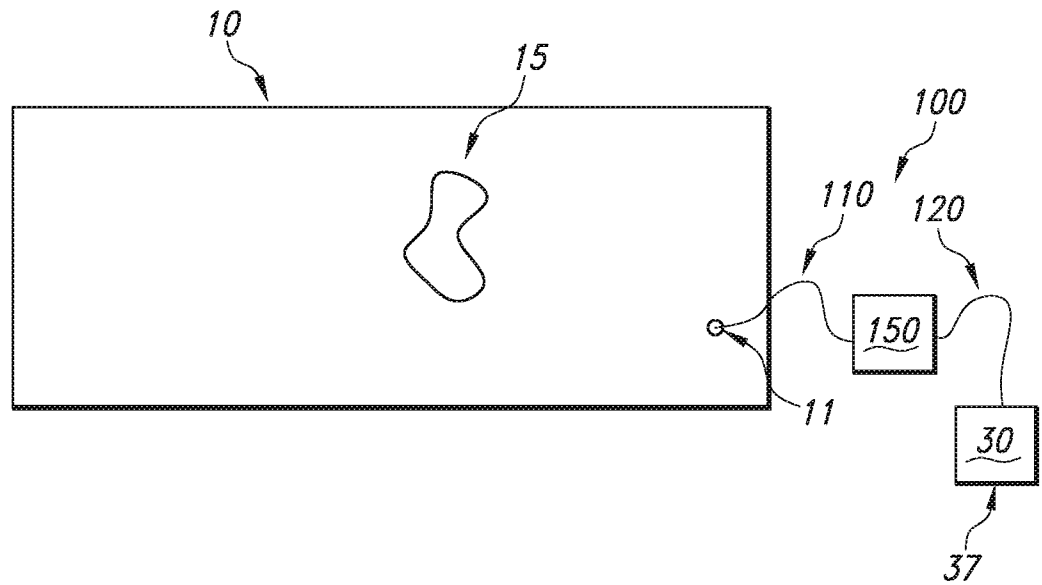


FIG. 1A

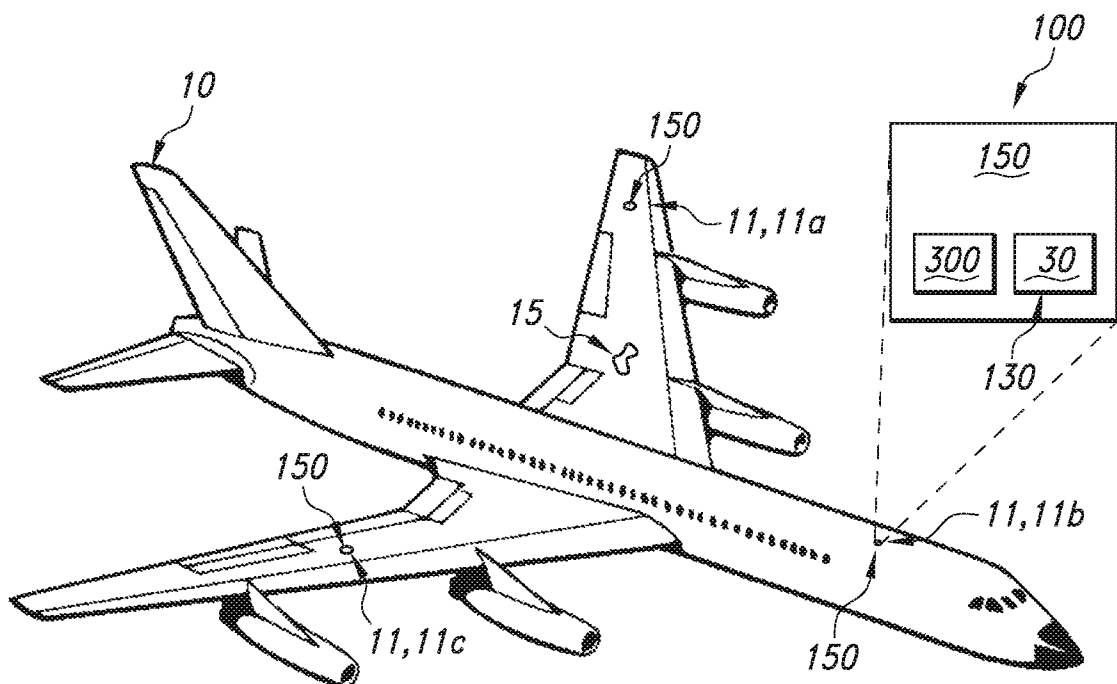


FIG. 1B

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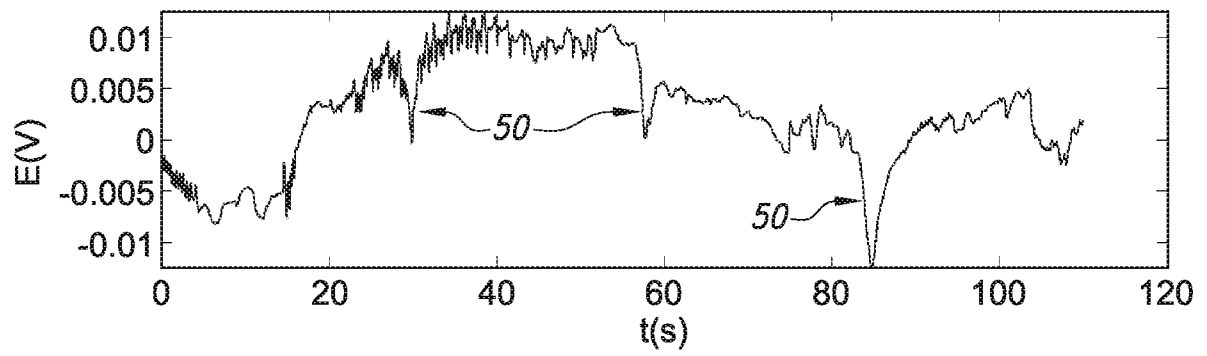


FIG. 2A

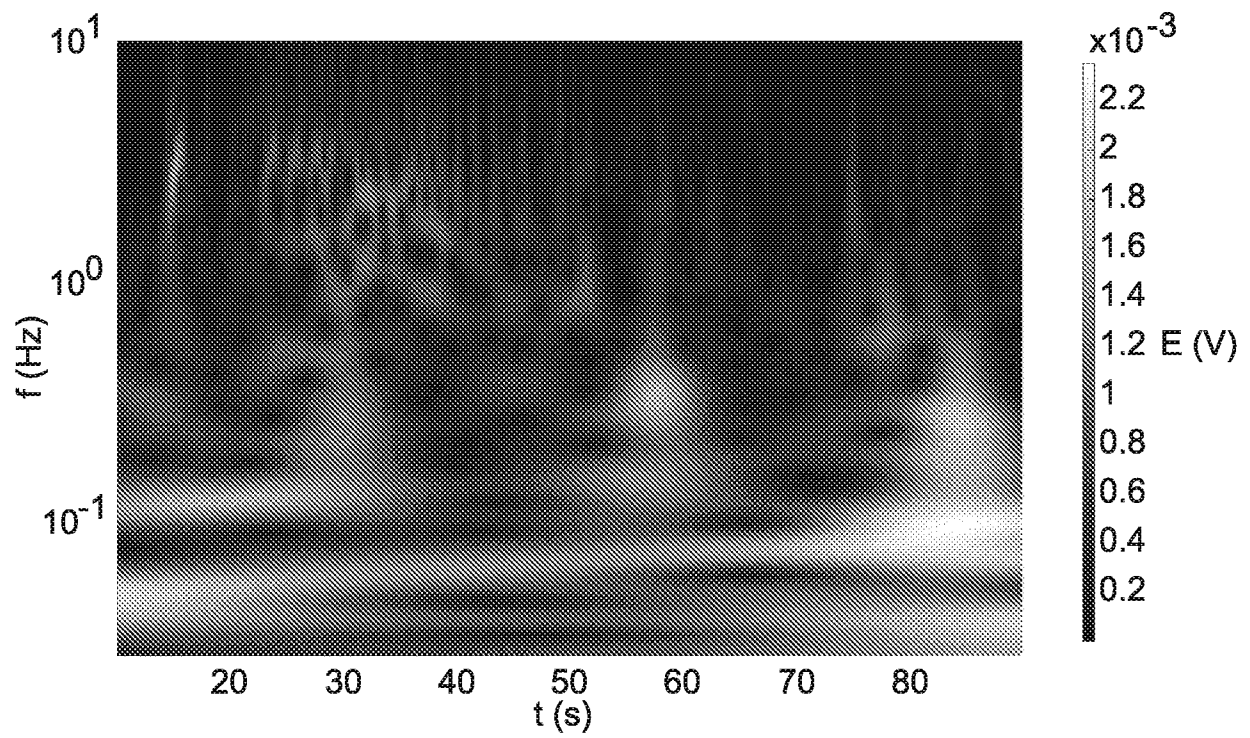


FIG. 2B

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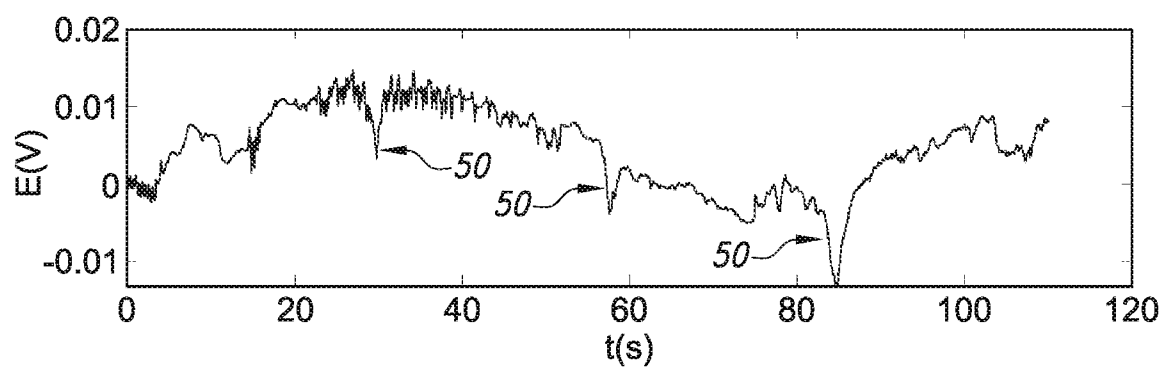


FIG. 2C

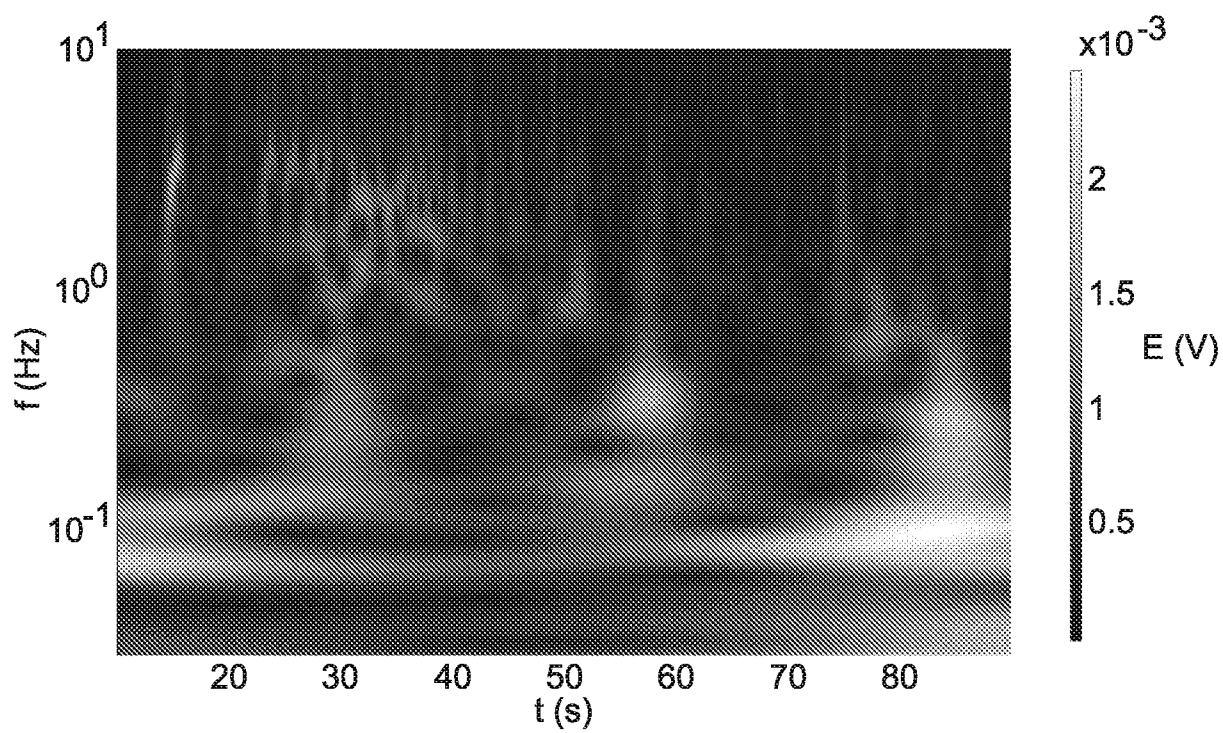


FIG. 2D

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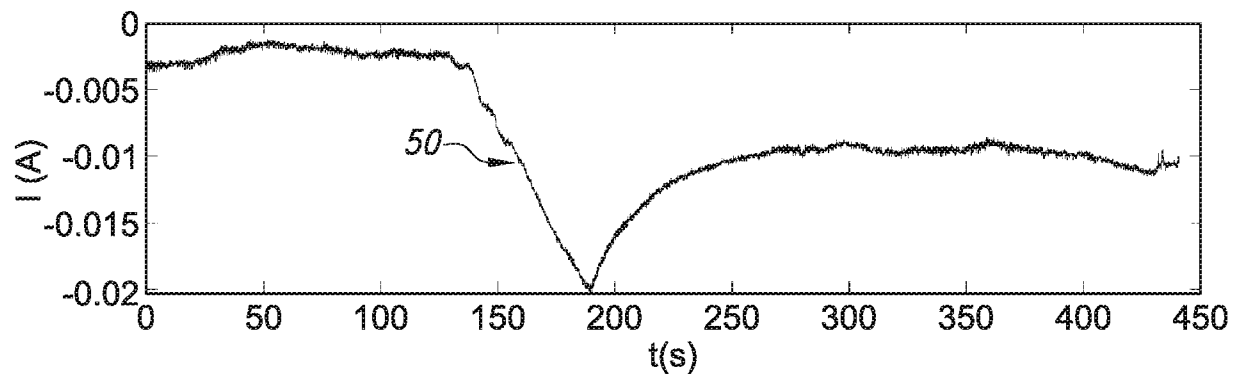


FIG. 3A

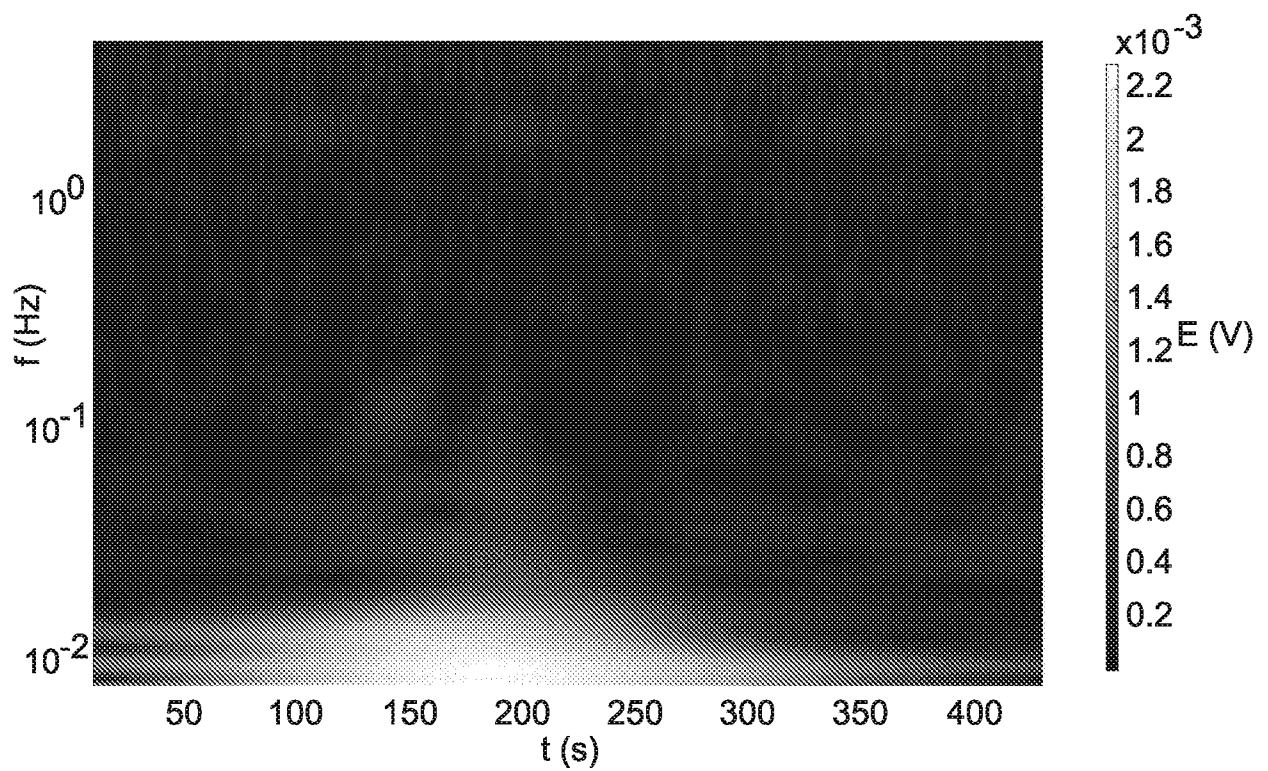


FIG. 3B

INTERNATIONAL SEARCH REPORT

International application No

PCT/NL2021/050177

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N17/02
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)
G01N

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, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	page 3, line 30 - page 4, line 3 figures 2,5	7,11-14
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A	----- EP 0 070 124 A2 (MCNAMEE DAVID FLEMING) 19 January 1983 (1983-01-19) page 6, line 5 - line 15 page 7, line 1 - line 3 figure 1 ----- -/-	1-15



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

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"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

8 June 2021

Date of mailing of the international search report

16/06/2021

Name and mailing address of the ISA/

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Authorized officer

Joyce, David

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2021/050177

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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