US012392797B2

(12) **United States Patent**
Sato

(10) **Patent No.: US 12,392,797 B2**
(45) **Date of Patent: Aug. 19, 2025**

(54) **INERTIAL MEASUREMENT DEVICE AND SELF-DIAGNOSIS METHOD OF INERTIAL MEASUREMENT DEVICE**

(71) Applicant: **SEIKO EPSON CORPORATION**, Tokyo (JP)

(72) Inventor: **Kenta Sato**, Shiojiri (JP)

(73) Assignee: **SEIKO EPSON CORPORATION** (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 293 days.

(21) Appl. No.: **18/324,253**

(22) Filed: **May 26, 2023**

(65) **Prior Publication Data**

US 2023/0384345 A1 Nov. 30, 2023

(30) **Foreign Application Priority Data**

May 30, 2022 (JP) 2022-087476

(51) **Int. Cl.**

G01P 21/00	(2006.01)
G01P 1/02	(2006.01)
G01P 15/097	(2006.01)

(52) **U.S. Cl.**

CPC ***G01P 21/00*** (2013.01); ***G01P 1/023*** (2013.01); ***G01P 15/097*** (2013.01)

(58) **Field of Classification Search**

CPC G01P 21/00; G01P 1/023; G01P 15/097; G01P 2015/0828; G01P 2015/0837; G01P 21/02

USPC 73/1.34, 1.38, 1.82

See application file for complete search history.

(56) **References Cited**

FOREIGN PATENT DOCUMENTS

CA	3062571 A1 *	6/2020	....	B23B 49/00
JP	2005-127890 A	5/2005		
KR	20200082395 A *	7/2020		

* cited by examiner

Primary Examiner — Robert R Raevis

(74) *Attorney, Agent, or Firm* — Harness, Dickey & Pierce, P.L.C.

(57) **ABSTRACT**

An inertial measurement device includes a first inertial sensor having a first detection axis, a second inertial sensor having a second detection axis defined in a direction opposite to the first detection axis, and a processing circuit configured to execute self-diagnosis based on whether a ratio of an amplitude of an output of the first inertial sensor to an amplitude of an output of the second inertial sensor is within a reference range.

7 Claims, 10 Drawing Sheets

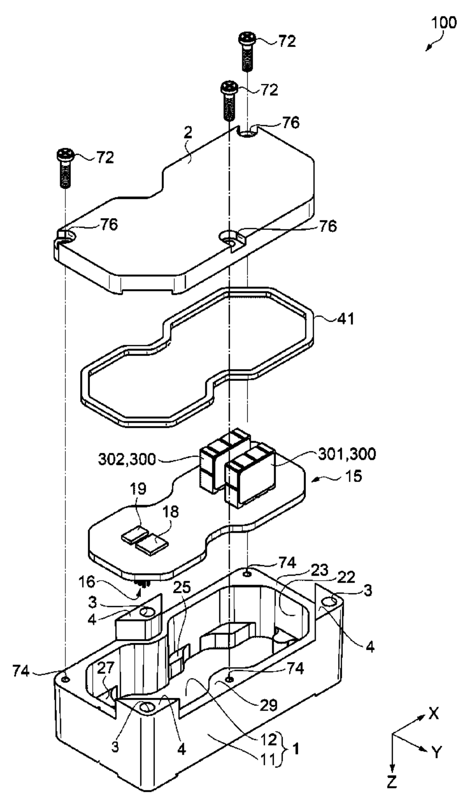


FIG. 1

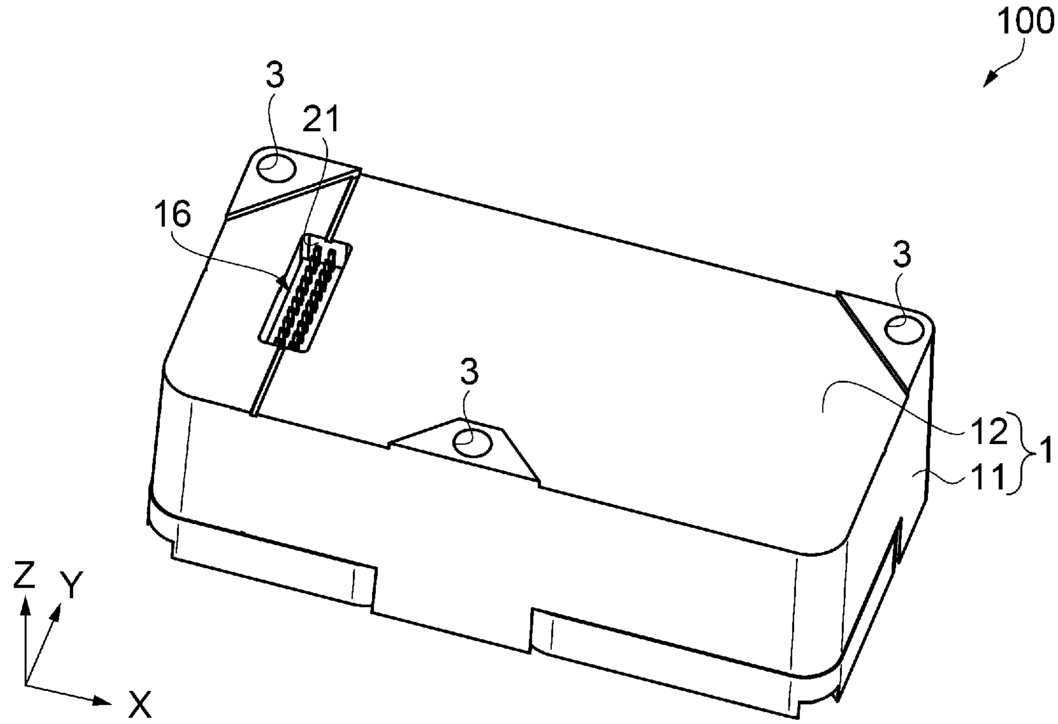


FIG. 2

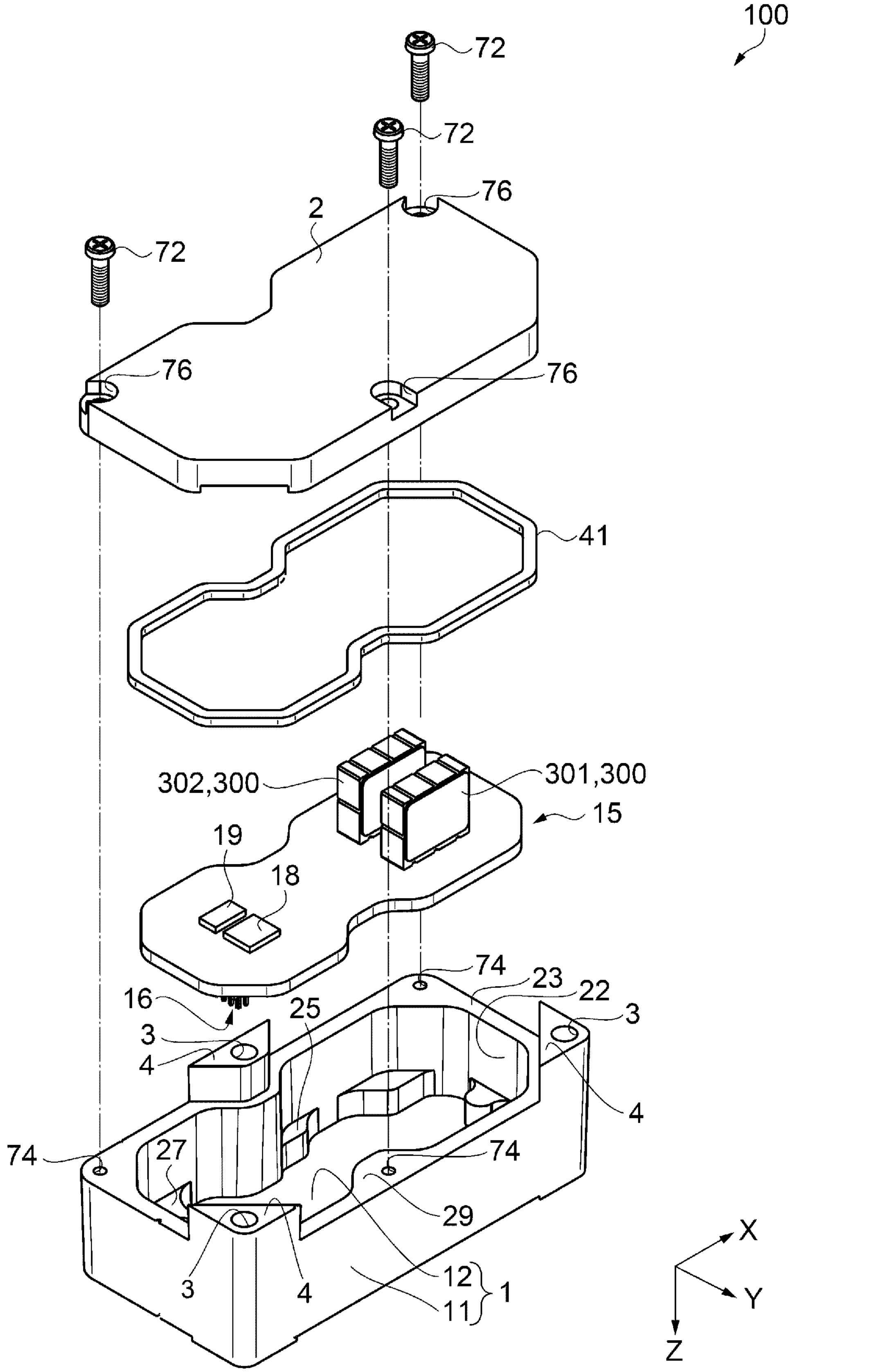

100
72
72
76
2
72
76
76
41
302,300
301,300
15
19
18
74
23
22
16
25
3
3
4
4
74
27
74
29
3
4
12
1
11
X
Y
Z

FIG. 3

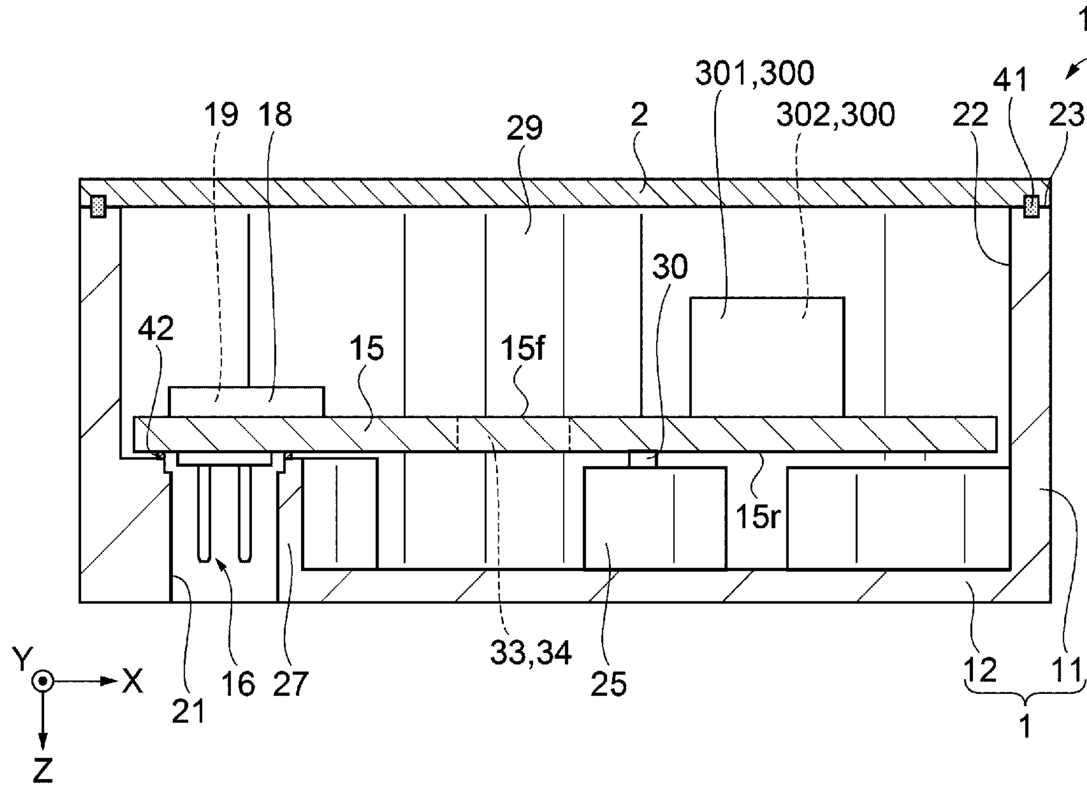

100
301,300
19 18
29
2
302,300
22
41
23
30
42
15
15f
15r
Y
X
Z
21
16
27
33,34
25
12
11
1

FIG. 4

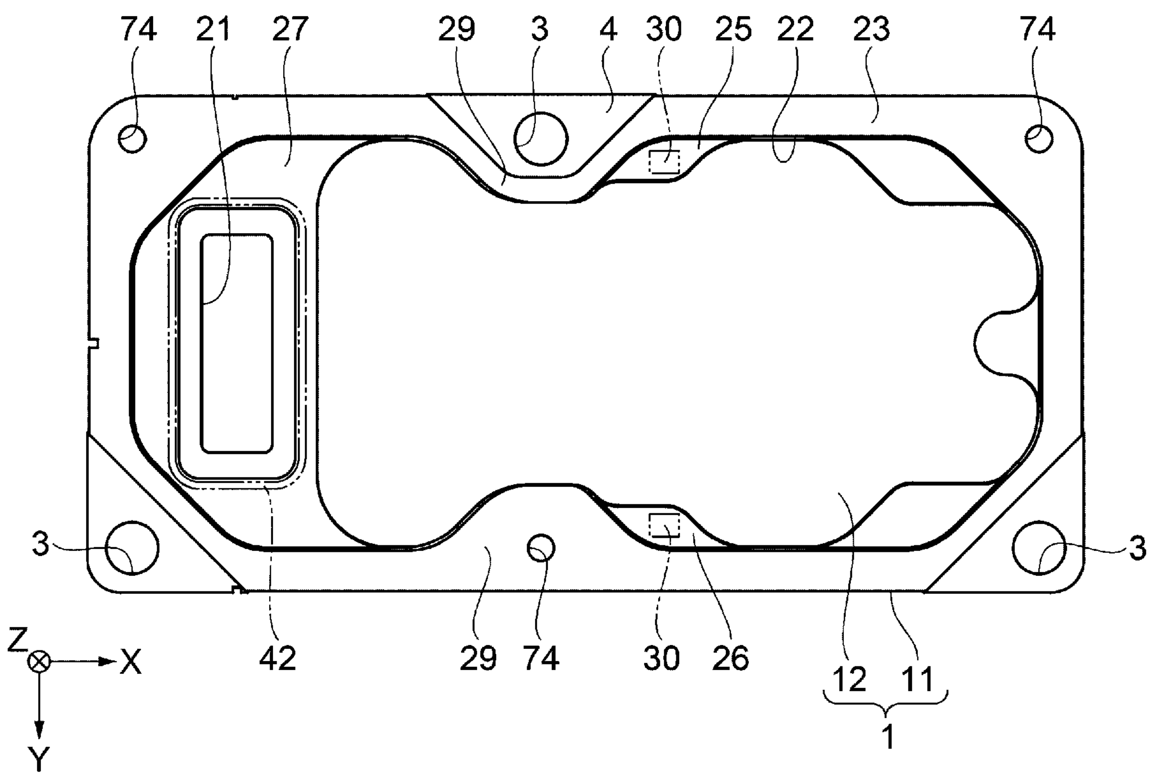

74
21
27
29
3
4
30
25
22
23
74
3
3
Z
X
Y
42
29
74
30
26
12
11
1

FIG. 5

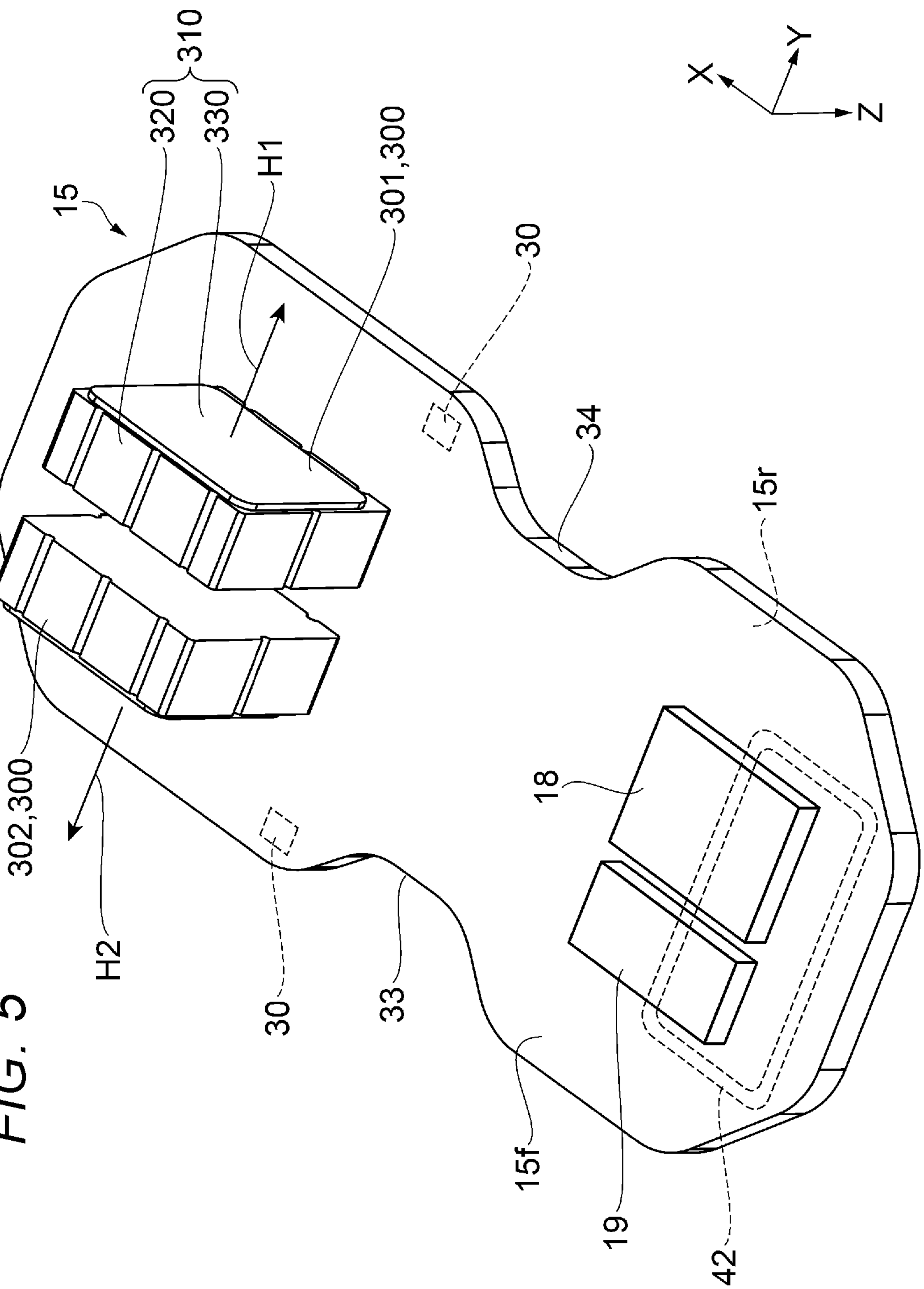

15
310
320
330
H1
301,300
30
34
15r
18
302,300
H2
30
33
15f
19
42
X
Y
Z

FIG. 6

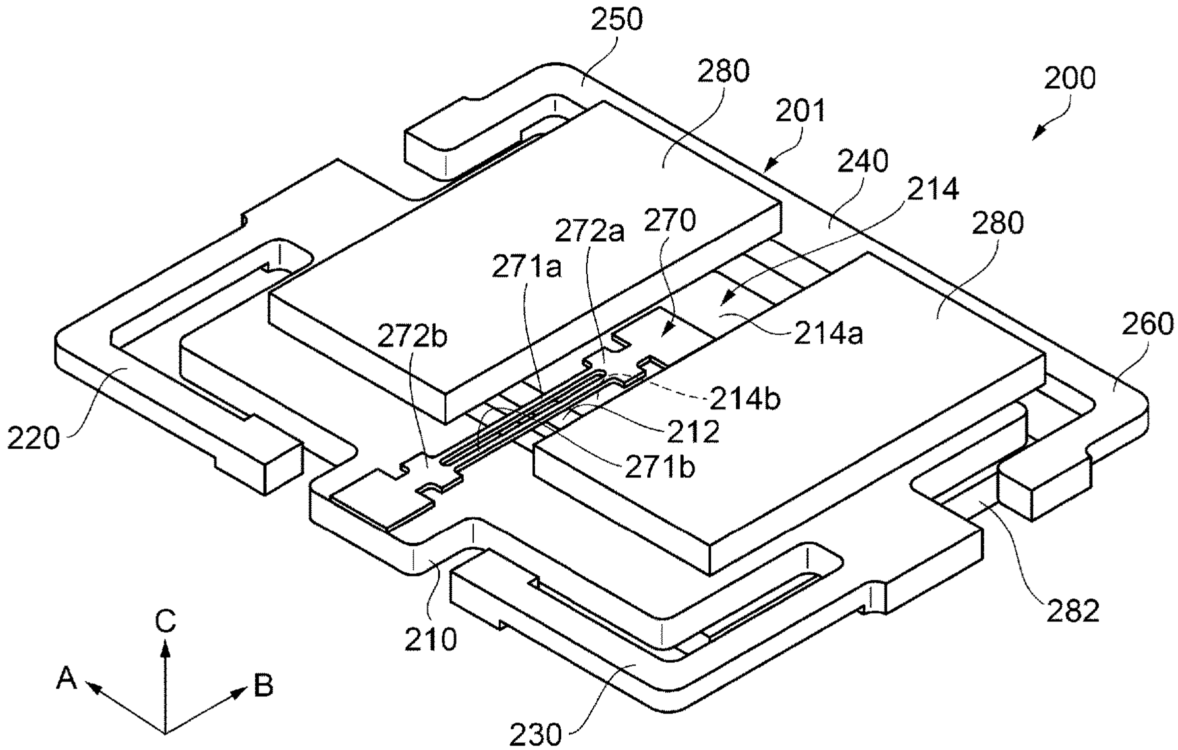
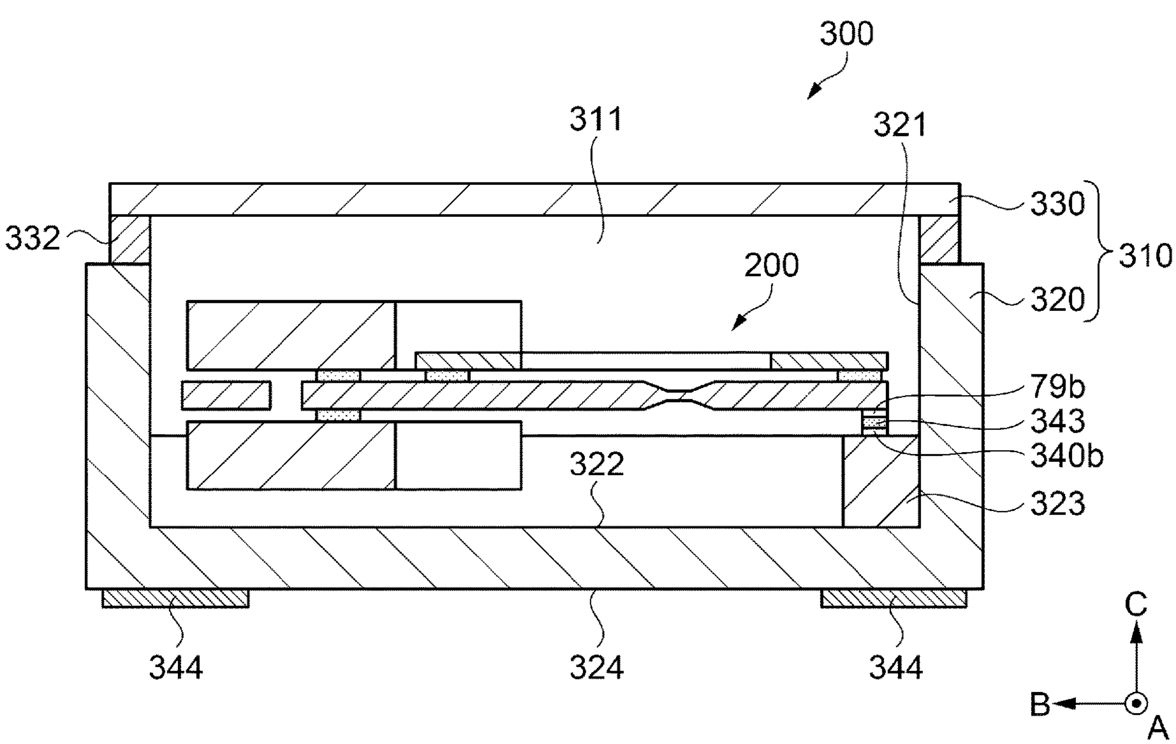

250
280
200
201
240
214
270
272a
280
271a
272b
214a
260
214b
212
220
271b
282
210
C
A
B
230

FIG. 7


300
311
321
332
330
310
200
320
79b
343
340b
322
323
344
324
344
C
B
A

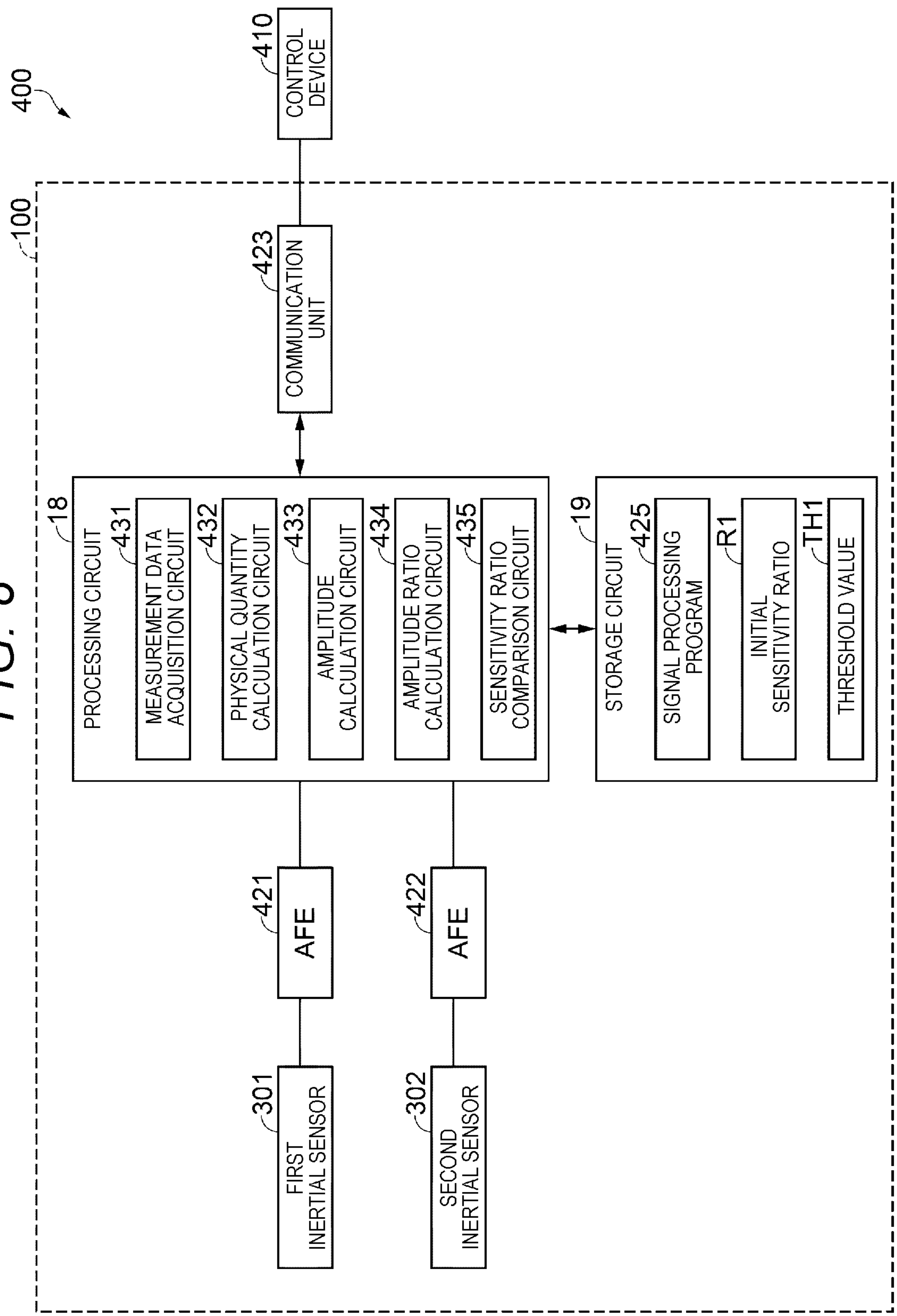
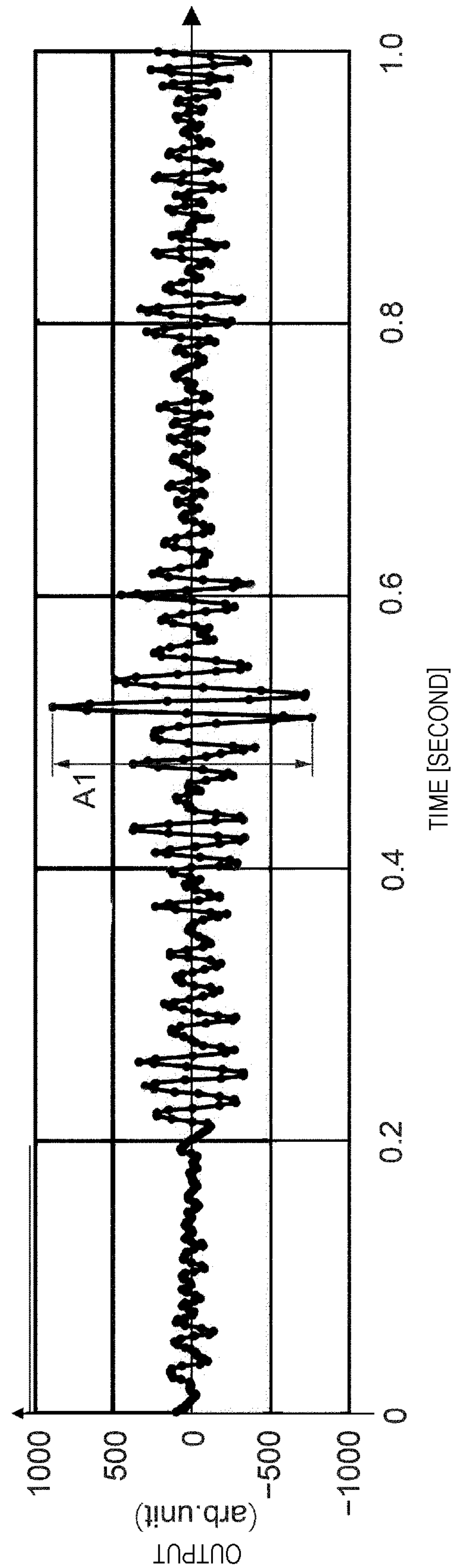

400
410
CONTROL DEVICE
100
423
COMMUNICATION UNIT
18
PROCESSING CIRCUIT
431
MEASUREMENT DATA ACQUISITION CIRCUIT
432
PHYSICAL QUANTITY CALCULATION CIRCUIT
433
AMPLITUDE CALCULATION CIRCUIT
434
AMPLITUDE RATIO CALCULATION CIRCUIT
435
SENSITIVITY RATIO COMPARISON CIRCUIT
19
STORAGE CIRCUIT
425
SIGNAL PROCESSING PROGRAM
R1
INITIAL SENSITIVITY RATIO
TH1
THRESHOLD VALUE
421
AFE
422
AFE
301
FIRST INERTIAL SENSOR
302
SECOND INERTIAL SENSOR

FIG. 8

FIG. 9A



A1
OUTPUT (arb.unit)
1000
500
0
−500
−1000
TIME [SECOND]
0
0.2
0.4
0.6
0.8
1.0

FIG. 9B

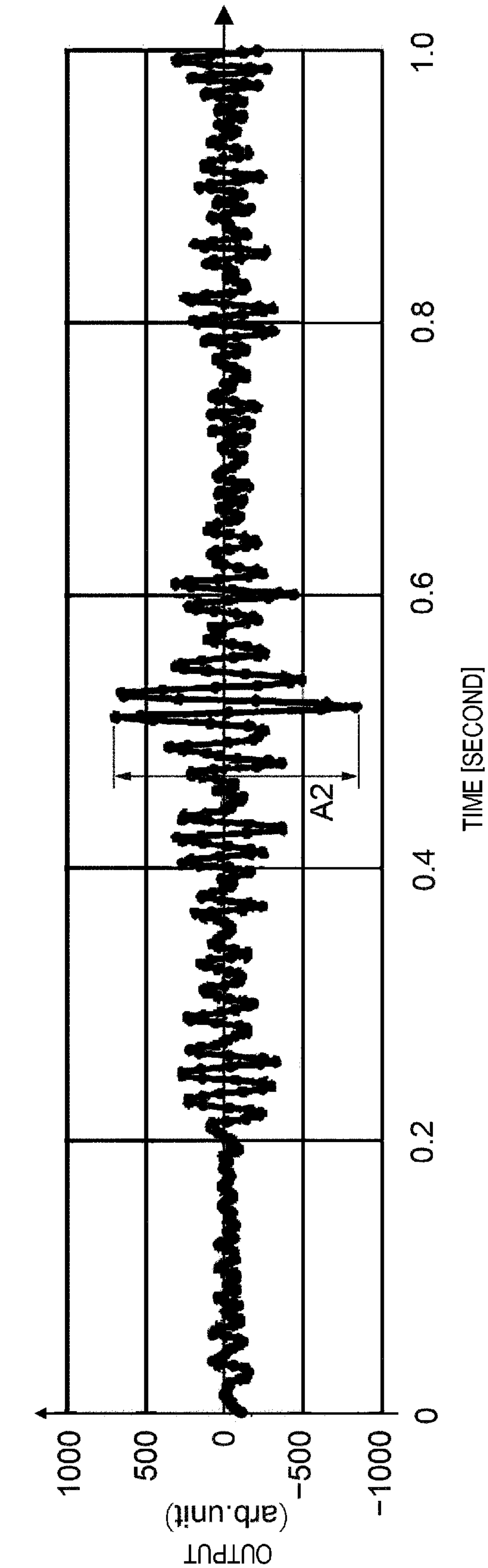

OUTPUT
(arb.unit)
1000
500
0
−500
−1000
0
0.2
0.4
0.6
0.8
1.0
A2
TIME [SECOND]

FIG. 10

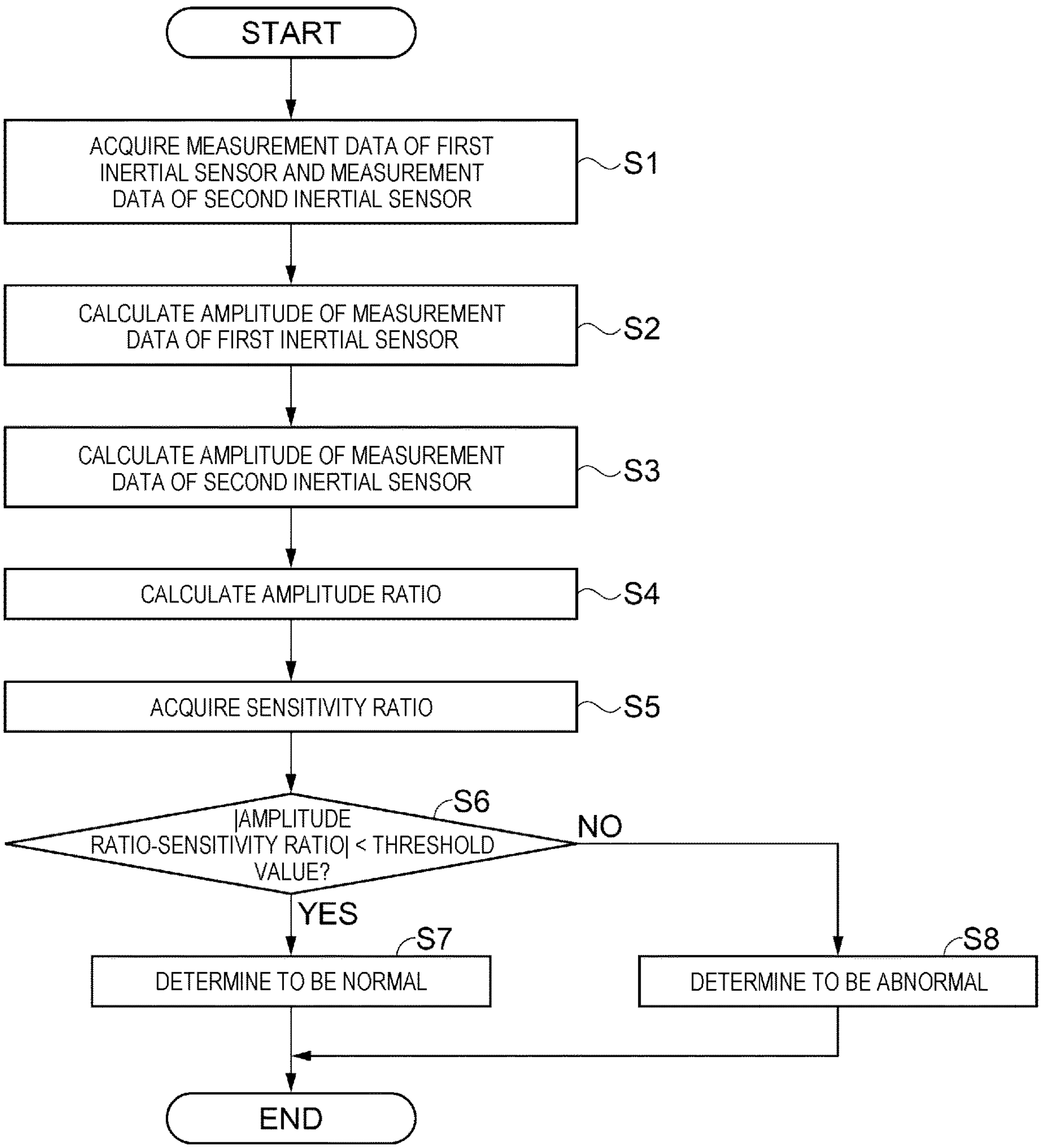
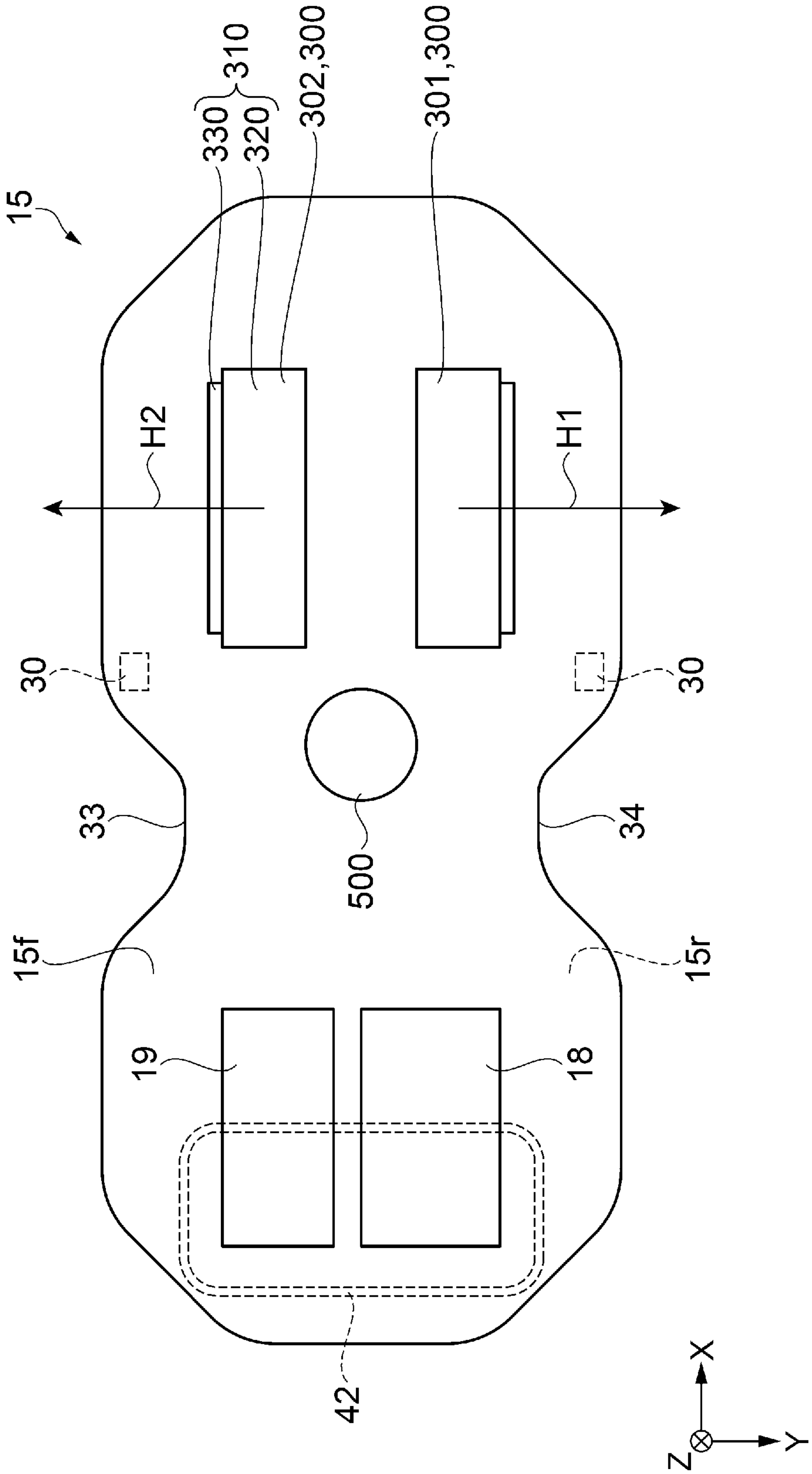

START
ACQUIRE MEASUREMENT DATA OF FIRST INERTIAL SENSOR AND MEASUREMENT DATA OF SECOND INERTIAL SENSOR
S1
CALCULATE AMPLITUDE OF MEASUREMENT DATA OF FIRST INERTIAL SENSOR
S2
CALCULATE AMPLITUDE OF MEASUREMENT DATA OF SECOND INERTIAL SENSOR
S3
CALCULATE AMPLITUDE RATIO
S4
ACQUIRE SENSITIVITY RATIO
S5
|AMPLITUDE RATIO-SENSITIVITY RATIO| < THRESHOLD VALUE?
S6
NO
YES
DETERMINE TO BE NORMAL
S7
DETERMINE TO BE ABNORMAL
S8
END

FIG. 11


15
330
320
310
302,300
301,300
H2
H1
30
30
33
34
500
15f
15r
19
18
42
X
Y
Z

INERTIAL MEASUREMENT DEVICE AND SELF-DIAGNOSIS METHOD OF INERTIAL MEASUREMENT DEVICE

The present application is based on, and claims priority from JP Application Serial Number 2022-087476, filed May 30, 2022, the disclosure of which is hereby incorporated by reference herein in its entirety.

BACKGROUND

1. Technical Field

The present disclosure relates to an inertial measurement device and a self-diagnosis method of an inertial measurement device.

2. Related Art

JP-A-2005-127890 discloses a technique in which, in an electrostatic capacitance detection type acceleration sensor, an electrostatic force is applied between a self-diagnosis electrode provided in a diaphragm outer frame and an electrode provided on a weight body so as to change an electrostatic capacitance between a diaphragm and a detection electrode and perform self-diagnosis by detecting the change in the electrostatic capacitance.

In the technique disclosed in JP-A-2005-127890, it is necessary to apply a voltage to the self-diagnosis electrode in order to displace the weight body. In such a technique, accuracy of self-diagnosis may decrease due to the self-diagnosis electrode and a configuration necessary for the self-diagnosis electrode.

SUMMARY

An inertial measurement device includes: a first inertial sensor having a first detection axis; a second inertial sensor having a second detection axis defined in a direction opposite to the first detection axis; and a processing circuit configured to execute self-diagnosis based on whether a ratio of an amplitude of an output of the first inertial sensor to an amplitude of an output of the second inertial sensor is within a reference range.

In a self-diagnosis method of an inertial measurement device including a first inertial sensor having a first detection axis, a second inertial sensor having a second detection axis defined in a direction opposite to the first detection axis, and a processing circuit configured to acquire an output of the first inertial sensor and an output of the second inertial sensor, the processing circuit executes self-diagnosis based on whether a ratio of an amplitude of the output of the first inertial sensor to an amplitude of the output of the second inertial sensor is within a reference range.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an inertial measurement device according to a first embodiment.

FIG. **2** is an exploded perspective view of the inertial measurement device.

FIG. **3** is a cross-sectional view of the inertial measurement device.

FIG. **4** is a plan view of a container.

FIG. **5** is a perspective view of a circuit board.

FIG. **6** is a perspective view of a sensor element.

FIG. **7** is a cross-sectional view of an inertial sensor using the sensor element.

FIG. **8** shows a configuration example of a measurement system including the inertial measurement device.

FIG. **9**A shows an example of a waveform of measurement data of a first inertial sensor.

FIG. **9**B shows an example of a waveform of measurement data of a second inertial sensor.

FIG. **10** is a flowchart showing an example of a procedure of a self-diagnosis method of the inertial measurement device.

FIG. **11** is a plan view of a circuit board provided in an inertial measurement device according to a third embodiment.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

Hereinafter, embodiments of the present disclosure will be described with reference to the drawings. For convenience of description, in FIGS. **1** to **5** and **11**, an X-axis, a Y-axis, and a Z-axis are shown as three axes orthogonal to each other. A coordinate system including the X-axis, the Y-axis, and the Z-axis is a reference coordinate system for describing an inertial measurement device **100** according to the present disclosure. In FIGS. **6** and **7**, an A-axis, a B-axis, and a C-axis are shown as three axes orthogonal to each other. A coordinate system including the A-axis, the B-axis, and the C-axis is a local coordinate system for describing an inertial sensor **300** according to the present disclosure.

A direction along the X-axis is also referred to as an "X-axis direction", a direction along the Y-axis is also referred to as a "Y-axis direction", a direction along the Z-axis is also referred to as a "Z-axis direction", a direction along the A-axis is also referred to as an "A-axis direction", a direction along the B-axis is also referred to as a "B-axis direction", and a direction along the C-axis is also referred to as a "C-axis direction". In addition, for example, a Y direction refers to a direction toward an arrow tip side along the Y-axis, and a −Y direction refers to a direction toward an arrow base side along the Y-axis. The Y-axis direction refers to both the Y direction and the −Y direction.

In addition, a plan view seen from a Z direction may be simply referred to as a "plan view".

1. First Embodiment

The inertial measurement device **100** according to a first embodiment will be described with reference to FIGS. **1** to **8**. First, a structure of the inertial measurement device **100** according to the first embodiment will be described with reference to FIGS. **1** to **5**. The inertial measurement device **100** is a measurement device that measures a physical quantity by using inertia. In the embodiment, the inertial measurement device **100** measures an acceleration in the Y-axis direction as an example of the physical quantity. However, the physical quantity measured by the inertial measurement device **100** is not limited thereto.

As shown in FIG. **1**, an outer shape of the inertial measurement device **100** is generally a rectangular parallelepiped shape having sides along the X-axis, the Y-axis, and the Z-axis, respectively. The inertial measurement device **100** has a substantially rectangular shape defined by a long side along the X-axis and a short side along the Y-axis in the plan view. The inertial measurement device **100** includes three screw holes **3** formed in the vicinity of both end portions of one long side and the vicinity of a center portion of the other long side in the plan view. By passing fixing screws through the respective screw holes **3**, the inertial measurement device **100** can be fixed to an attachment surface of an attachment target body. The inertial measurement device **100** is used in a state of being fixed to the attachment target body which is a vibration measurement target. The attachment target body is, for example, a structure such as a building or a bridge, or a moving body such as an automobile, a drone, or a robot.

The inertial measurement device **100** includes an opening portion **21** provided in a surface facing the Z direction. A connector **16** of a plug type is disposed inside the opening portion **21**. The connector **16** includes a plurality of pins disposed in two rows, and the plurality of pins are arranged in the Y direction in each row. A connector (not shown) of a socket type is coupled to the connector **16**. Through the connector **16**, transmission and reception of a signal such as a drive voltage of the inertial measurement device **100** or a measured value output from the inertial measurement device **100** are performed between the inertial measurement device **100** and the attachment target body or a control device (not shown).

As shown in FIGS. **2** and **3**, the inertial measurement device **100** includes a container **1**, a lid portion **2**, a seal member **41**, a circuit board **15**, and the like. The circuit board **15** is a board in the present disclosure. Specifically, the circuit board **15** is attached to an inner side of the container **1** via fixing members **30** and **42**. The lid portion **2** covers an opening of the container **1** via the seal member **41**. The lid portion **2** is fixed, by a screw **72** inserted into a through hole **76** provided in the lid portion **2** and a female screw **74** provided in the container **1**, to the container **1** via the seal member **41**.

The container **1** accommodates the circuit board **15**. The container **1** has a box shape opened toward a –Z direction. An outer shape of the container **1** is substantially a rectangular parallelepiped shape, and a metal material such as aluminum can be adopted as a material of the container **1** that forms a part of the outer shape of the inertial measurement device **100**.

The container **1** includes a flat plate-shaped bottom portion **12** and a frame-shaped side wall **11** erected in the –Z direction from an outer peripheral portion of the bottom portion **12**. Inside of the container **1** can be defined as a space surrounded by the bottom portion **12** and the side wall **11**. The circuit board **15** is disposed such that an outer edge thereof extends along an inner surface **22** of the side wall **11**. The lid portion **2** is fixed to an opening surface **23** so as to cover the opening of the container **1**. The opening surface **23** coincides with an end surface of the side wall **11** on which the lid portion **2** is placed. On the opening surface **23**, three fixed protruding portions **4** are erected in the vicinity of both end portions of one long side and the vicinity of a center portion of the other long side of the container **1** in the plan view. In addition, in the opening surface **23**, three female screws **74** are provided in the vicinity of a center of the one long side and the vicinity of both end portions of the other long side of the container **1** in the plan view. The screw hole **3** is formed in each of the fixed protruding portions **4**.

In addition, as shown in FIGS. **3** and **4**, the side wall **11** includes two protruding portions **29** each protruding inward in a ridge shape from the bottom portion **12** to the opening surface **23**. The two protruding portions **29** are located in the vicinity of the center portion of the one long side and the vicinity of the center portion of the other long side of the container **1** in the plan view. The two protruding portions **29** correspond to constricted portions **33** and **34** of the circuit board **15** to be described later.

In addition, the container **1** includes a first pedestal **27** and second pedestals **25** and **26** protruding, in a stepped shape higher by one step, from the bottom portion **12** toward the opening surface **23**. The first pedestal **27** is provided in a region including a region in which the connector **16** attached to the circuit board **15** is disposed in the plan view. The container **1** includes the opening portion **21** provided in the first pedestal **27** in the plan view. The opening portion **21** penetrates the inside and the outside of the container **1**. The connector **16** is inserted into the opening portion **21**.

The second pedestals **25** and **26** are located on a side opposite to the first pedestal **27** with respect to the two protruding portions **29**. The first pedestal **27** and the second pedestals **25** and **26** function as pedestals for fixing the circuit board **15** to the container **1**.

A planar shape of the outer shape of the container **1** is not limited to the rectangular shape and may be a polygonal shape such as a square shape, a hexagonal shape, or an octagonal shape. In addition, a corner of an apex portion of the polygon may be chamfered, or any one of sides of the polygon may have a curved planar shape. In addition, a planar shape of inside of the container **1** is not limited to the shape described above and may be another shape. In addition, planar shapes of the outer shape and the inside of the container **1** may be similar or may not be similar.

The circuit board **15** that serves as the board is a multilayer board in which a plurality of through holes and the like are formed. In the embodiment, a glass epoxy board is used as the circuit board **15**. The circuit board **15** is not limited to the glass epoxy board, and a composite board or a ceramic board may be used.

As shown in FIGS. **3** and **5**, the circuit board **15** has a flat plate shape having a first surface **15*f*** and a second surface **15*r***, which are planes along the X direction and the Y direction, and a thickness along the Z direction. The first surface **15*f*** and the second surface **15*r*** have a front and back relationship with each other. The first surface **15*f*** is a surface on the opening side of the container **1**, and the second surface **15*r*** is a surface on the bottom portion **12** side.

The circuit board **15** includes the constricted portions **33** and **34** at a center thereof in the X-axis direction in the plan view. The constricted portions **33** and **34** are constricted toward the center of the circuit board **15** on both sides in the Y-axis direction of the circuit board **15** in the plan view.

The circuit board **15** is inserted into an internal space of the container **1** with the second surface **15*r*** facing the first pedestal **27** and the second pedestals **25** and **26**. The circuit board **15** is fixed to the container **1** by being supported by the first pedestal **27** and the second pedestals **25** and **26**. Specifically, the circuit board **15** is mechanically coupled to the first pedestal **27** via the fixing member **42** disposed in a ring shape around the connector **16** and is mechanically coupled to the second pedestals **25** and **26** via the fixing member **30**. In the embodiment, the fixing member and the fixing member **42** are adhesives.

Two inertial sensors **300**, a processing circuit **18**, a storage circuit **19**, other electronic components (not shown), and the like are disposed on the first surface **15*f*** of the circuit board **15**. The connector **16** is disposed on the second surface **15*r*** of the circuit board **15**. The processing circuit **18**, the storage circuit **19**, the two inertial sensors **300**, and the connector **16** are electrically coupled to each other via a wiring (not shown). Although not shown, the circuit board **15** may be provided with another wiring or another terminal electrode. In addition, although the processing circuit **18** is disposed on the first surface 15*f* of the circuit board **15** in the embodiment, the processing circuit **18** may be disposed on the second surface **15***r*. The storage circuit **19** is disposed on the first surface **15***f* of the circuit board **15**, and may be disposed on the second surface **15***r*.

The inertial sensor **300** is a sensor that detects a physical quantity by using inertia. In the embodiment, the inertial sensor **300** is an acceleration sensor capable of detecting an acceleration in one axial direction as the physical quantity. However, the inertial sensor **300** is not limited to the acceleration sensor and may be a sensor capable of detecting information related to inertia by a well-known detection method. For example, the inertial sensor **300** may be an angular velocity sensor. In addition, a sensor capable of detecting a physical quantity in multiaxial directions of 2 or more axes may be used. A structure or disposition of the inertial sensor **300** will be described later.

One of the two inertial sensors **300** disposed on the first surface **15***f* of the circuit board **15** is a first inertial sensor **301**, and the other is a second inertial sensor **302**. The first inertial sensor **301** detects an acceleration of a first detection axis H**1**. The second inertial sensor **302** detects an acceleration of a second detection axis H**2**. The second detection axis H**2** of the second inertial sensor **302** is defined in a direction opposite to the first detection axis H1 of the first inertial sensor **301**. That is, a positive direction of one of the first detection axis H**1** and the second detection axis H**2** is the same as a negative direction of the other axis. Therefore, a detection value of the second inertial sensor **302** is in opposite phase to a detection value of the first inertial sensor **301**.

In the embodiment, the first detection axis H**1** of the first inertial sensor **301** and the second detection axis H**2** of the second inertial sensor **302** are detection axes along the Y-axis direction. Specifically, the first detection axis H**1** of the first inertial sensor **301** is a detection axis in the Y direction, and the second detection axis H**2** of the second inertial sensor **302** is a detection axis in the −Y direction. More specifically, the first detection axis H**1** is a detection axis whose positive direction is the Y direction and whose negative direction is the −Y direction. The second detection axis H2 is a detection axis whose positive direction is the −Y direction and whose negative direction is the Y direction. Accordingly, for example, the positive direction of the first detection axis H1 and the negative direction of the second detection axis H**2** are the same.

The first inertial sensor **301** detects an acceleration on the first detection axis H**1** and sequentially outputs an output signal corresponding to a detection value to the processing circuit **18**. The second inertial sensor **302** detects an acceleration on the second detection axis H2 and sequentially outputs an output signal corresponding to a detection value to the processing circuit **18**.

The processing circuit **18** controls each unit necessary for operating the inertial measurement device **100**. The processing circuit **18** is, for example, a central processing unit (CPU) or a digital signal processor (DSP). The processing circuit **18** executes a program stored in the storage circuit **19**. Accordingly, the processing circuit **18** acquires the output signal output from the first inertial sensor **301** and the output signal output from the second inertial sensor **302** and performs signal processing.

The storage circuit **19** stores programs and data. The storage circuit **19** is a computer-readable storage medium such as a read-only memory (ROM) or a random access memory (RAM).

Although the processing circuit **18** and the storage circuit **19** are separate from each other in the embodiment, the processing circuit **18** and the storage circuit **19** may also be integrated. For example, the processing circuit **18** may be a micro-controller unit (MCU) including a CPU and the storage circuit **19**.

The processing circuit **18** calculates a differential value that is a difference between a detection value of one inertial sensor **300** of the two inertial sensors **300** and a detection value of the other inertial sensor **300**. By calculating the differential value, it is possible to amplify the detection value while canceling out in-phase error factors. Examples of the in-phase error factors include electrical noises and temperature characteristics of the inertial sensor **300**.

Specifically, the processing circuit **18** generates, based on the output signal as the detection value of the first inertial sensor **301** and the output signal as the detection value of the second inertial sensor **302**, a differential signal as a differential value that is a difference between the detection value of the first inertial sensor **301** and the detection value of the second inertial sensor **302**. The differential signal generated by the processing circuit **18** is output to an external device coupled to the inertial measurement device **100** via the connector **16**. In the embodiment, the differential signal output from the inertial measurement device **100** corresponds to a measurement value of an acceleration in the Y-axis direction measured by the inertial measurement device **100**.

The structure of the inertial measurement device **100** has been described above. Next, a structure of the inertial sensor **300** provided in the above-described inertial measurement device **100** will be described with reference to FIGS. **6** and **7**.

In the embodiment, the inertial sensor **300** is a frequency-variable type acceleration sensor. The frequency-variable type acceleration sensor includes a sensor element including a vibration element. The sensor element is configured to change a force applied to the vibration element according to an acceleration. When the force applied to the vibration element changes, a resonance frequency of the vibration element changes according to the force applied to the vibration element. In this way, by detecting the resonance frequency of the vibration element according to the acceleration, the frequency-variable type acceleration sensor can detect the acceleration.

As shown in FIG. **7**, the inertial sensor **300** includes a sensor element **200** and a package **310**. An accommodation space **311** that accommodates the sensor element **200** is defined in the package **310**. In the embodiment, first, the sensor element **200** will be described with reference to FIG. **6**, and then the inertial sensor **300** using the sensor element **200** will be described with reference to FIG. **7**.

As shown in FIG. **6**, the sensor element **200** includes a board structure **201** including a base portion **210** and the like, a vibration element **270** that is supported by the board structure **201** and detects an acceleration, and mass portions **280** and **282**.

The board structure **201** has a flat plate shape having two main surfaces along an A-B plane orthogonal to the C-axis. The board structure **201** includes the base portion **210**, a movable portion **214**, a coupling portion **240**, and four support portions coupled to the base portion **210**. The four support portions are a first support portion **220**, a second support portion **230**, a third support portion **250**, and a fourth support portion **260**. Each support portion has an arm shape bent at a right angle along the A-axis and the B-axis. In the embodiment, the board structure **201** is formed of a quartz crystal board. The board structure **201** may be formed of a material other than quartz crystal.

The base portion **210** is coupled to the movable portion **214** via a groove-shaped joint portion **212** along the A-axis, thereby swingably supporting the movable portion **214**. The base portion **210** has a U shape bent at a right angle in a plan view seen from the C-axis direction. The coupling portion **240** couples both ends of the U shape formed by the base portion **210**. Accordingly, the base portion **210** and the coupling portion **240** form a substantial frame shape in the plan view. The first support portion **220** and the second support portion **230** are coupled to both sides of the base portion **210** in the A-axis direction. The third support portion **250** and the fourth support portion **260** are coupled to the base portion **210** at the vicinity of the coupling portion **240**.

The joint portion **212** is provided between the base portion **210** and the movable portion **214** and couples the base portion **210** and the movable portion **214**. The joint portion **212** is thinner than the base portion **210** and the movable portion **214**. The joint portion **212** is formed in a constricted shape on both sides in the C-axis direction in a cross-sectional view seen from the A-axis direction. Therefore, the joint portion **212** that is thinner than the base portion **210** and the movable portion **214** functions as a fulcrum, that is, an intermediate hinge when the movable portion **214** is displaced with respect to the base portion **210**.

The movable portion **214** is coupled to the base portion **210** via the joint portion **212**. The movable portion **214** has a flat plate shape and has main surfaces **214***a* and **214***b* that face each other and that have a front and back relationship in the C-axis direction. The movable portion **214** is displaced in the C-axis direction with the joint portion **212** as a fulcrum according to an acceleration of a C-axis component. That is, the joint portion **212** and the movable portion **214** function as a cantilever.

The coupling portion **240** is disposed on a side of the movable portion **214** opposite to the joint portion **212** side, that is, in the B direction of the movable portion **214**. The coupling portion **240** extends in the A-axis direction from one end portion of the base portion **210** where the third support portion **250** is provided to the other end portion of the base portion **210** where the fourth support portion **260** is provided.

The first support portion **220** and the second support portion **230** are provided symmetrically with respect to a center line of the vibration element **270** along the B-axis in the plan view. In addition, similarly, the third support portion **250** and the fourth support portion **260** are provided symmetrically with respect to the center line of the vibration element **270** along the B-axis in the plan view. A distal end portion of each of the first support portion **220**, the second support portion **230**, the third support portion **250**, and the fourth support portion **260** is coupled to an inner side of the package **310**. Accordingly, the first support portion **220**, the second support portion **230**, the third support portion **250**, and the fourth support portion **260** support the board structure **201** in the accommodation space **311** of the package **310**.

Both ends of the vibration element **270** are coupled to the base portion **210** and the movable portion **214** of the board structure **201**. In other words, the vibration element **270** is provided across the base portion **210** and the movable portion **214** to straddle the joint portion **212**.

In the embodiment, the vibration element **270** is formed of a quartz crystal board. The vibration element **270** may be formed of a piezoelectric material other than quartz crystal. However, the vibration element **270** and the board structure **201** are preferably formed of the same material. Accordingly, since a difference between a linear expansion coefficient of the board structure **201** and a linear expansion coefficient of the vibration element **270** is small, it is possible to reduce a stress applied from the board structure **201** to the vibration element **270** caused by the difference in the linear expansion coefficient.

In the embodiment, the vibration element **270** is a double-tuning-fork type vibration element including two vibration beam portions **271***a* and **271***b* each along the B-axis, and a first base portion **272***a* and a second base portion **272***b* terminating both ends of each of the vibration beam portions **271***a* and **271***b*. The first base portion **272***a* is coupled to the movable portion **214**. The second base portion **272***b* is coupled to the base portion **210** of the board structure **201**. The vibration element **270** includes electrodes (not shown) provided on a surface thereof, for example, an excitation electrode and an extraction electrode. When a drive signal with an AC voltage is applied to the excitation electrode (not shown) provided on the vibration beam portions **271***a* and **271***b*, the vibration beam portions **271***a* and **271***b* perform flexural vibration in the A-axis direction so as to be separated from each other or approach each other.

Although the vibration element **270** is a double-tuning-fork type vibration element in the embodiment, the vibration element **270** is not limited to the double-tuning-fork type vibration element. For example, the vibration element **270** may be a single beam vibration element including one vibration beam portion.

The mass portions **280** and **282** are provided on the main surfaces **214***a* and **214***b* of the movable portion **214**. Specifically, two mass portions **280** are provided on the main surface **214***a* via a bonding material (not shown). On the other hand, two mass portions **282** are provided on the main surface **214***b* via a bonding material (not shown). The mass portions **280** and **282** may be formed of a metal such as copper (Cu) or gold (Au).

In the sensor element **200** configured as described above, for example, when an acceleration in the C direction is applied, the movable portion **214** is displaced in the −C direction with the joint portion **212** as a fulcrum. Accordingly, a force in a direction in which the first base portion **272***a* and the second base portion **272***b* are separated from each other along the B-axis is applied to the vibration element **270**, and a tensile stress is generated in the vibration beam portions **271***a* and **271***b*. Therefore, resonance frequencies of the vibration beam portions **271***a* and **271***b* increase. On the other hand, when an acceleration in the −C direction is applied to the sensor element **200**, the movable portion **214** is displaced in the C direction with the joint portion **212** as a fulcrum. Accordingly, a force in a direction in which the first base portion **272***a* and the second base portion **272***b* approach each other along the B-axis is applied to the vibration element **270**, and a compressive stress is generated in the vibration beam portions **271***a* and **271***b*. Therefore, the resonance frequencies of the vibration beam portions **271***a* and **271***b* decrease.

In this way, the sensor element **200** can detect an acceleration in the C-axis direction based on a resonance frequency of the vibration element **270**. In other words, the sensor element **200** configured as described above is a frequency-variable type acceleration sensor element whose detection axis is the C-axis.

Next, the inertial sensor **300** using the above-described sensor element **200** will be described. As shown in FIG. **7**, the inertial sensor **300** includes the sensor element **200** and the package **310**. The package **310** includes a package base **320** and a lid **330**.

The package base **320** has a box shape including a recessed portion **321** opened toward the C direction. The lid **330** has a flat plate shape. The lid **330** is coupled to the package base **320** via a lid bonding member **332** so as to close the opening of the recessed portion **321**. By closing the opening of the recessed portion **321** by the lid **330**, the accommodation space **311** in which the sensor element **200** is accommodated is formed. The accommodation space **311** is hermetically sealed.

The package base **320** includes a step portion **323** protruding from an inner bottom surface **322** of the package base **320** toward the lid **330**. For example, the step portion **323** is provided in a frame shape along an inner wall of the package base **320**. The step portion **323** is provided with a plurality of internal terminals **340***b*.

The plurality of internal terminals **340***b* are coupled to the first support portion **220**, the second support portion **230**, the third support portion **250**, and the fourth support portion **260** of the sensor element **200**. Specifically, each of the first support portion **220**, the second support portion **230**, the third support portion **250**, and the fourth support portion **260** is provided with a fixing portion coupling terminal **79***b*. The fixing portion coupling terminal **79***b* and the internal terminal **340***b* are disposed to face each other so as to overlap each other in the plan view seen from the C-axis direction. The fixing portion coupling terminal **79***b* and the internal terminal **340***b* are electrically and mechanically coupled to each other via a conductive adhesive **343**. In this way, the sensor element **200** is mounted to the package **310** in the accommodation space **311** of the package **310**.

The package base **320** includes an external terminal **344** provided on an outer bottom surface **324**. The external terminal **344** is electrically coupled to the internal terminal **340***b* via an internal wiring (not shown). In addition, for example, as shown in FIG. **5**, when the inertial sensor **300** is disposed on the first surface **15***f* of the circuit board **15**, the external terminal **344** is electrically coupled to a wiring (not shown) provided on the circuit board **15**. The external terminal **344** may be provided not only on the outer bottom surface **324** but also on an outer wall of the package base **320**.

In the inertial sensor **300** having such a configuration, when a drive signal is applied to an excitation electrode of the sensor element **200** via the external terminal **344**, the internal terminal **340***b*, the fixing portion coupling terminal **79***b*, and the like, the vibration beam portions **271***a* and **271***b* of the sensor element **200** resonate at a predetermined frequency. Then, the inertial sensor **300** outputs, as an output signal, a resonance frequency of the sensor element **200** that changes according to an acceleration.

The inertial sensor **300** configured as described above is a frequency-variable type acceleration sensor whose detection axis is the C-axis. By matching the C-axis which is the detection axis of the inertial sensor **300** with a desired direction, the inertial sensor **300** can detect an acceleration in the desired direction.

The structure of the inertial sensor **300** has been described above. Next, referring back to FIG. **5**, a disposition of the inertial sensor **300** will be described. For example, as shown in FIG. **5**, when a side surface of the package **310** is opposite to the first surface **15***f* of the circuit board **15** and the inertial sensor **300** is vertically mounted on the circuit board **15** (upright mounting), the C-axis which is the detection axis of the inertial sensor **300** is along the first surface **15***f* of the circuit board **15**.

Specifically, the first inertial sensor **301** is mounted such that the C-axis of the first inertial sensor **301**, that is, the positive direction of the first detection axis H**1** of the first inertial sensor **301** coincides with the Y direction in a state in which the first inertial sensor **301** is mounted upright on the first surface **15***f* of the circuit board **15**. In addition, the second inertial sensor **302** is mounted such that the C-axis of the second inertial sensor **302**, that is, the positive direction of the second detection axis H**2** of the second inertial sensor **302** coincides with the −Y direction in a state in which the second inertial sensor **302** is mounted upright on the first surface **15***f* of the circuit board **15**. In other words, the first inertial sensor **301** has the first detection axis H**1** along the circuit board **15**, and the second inertial sensor **302** has the second detection axis H**2** defined in the direction opposite to the first detection axis H**1**.

In this way, by mounting the first inertial sensor **301** and the second inertial sensor **302** on the circuit board the first inertial sensor **301** and the second inertial sensor **302** can detect an acceleration in the Y-axis direction. The detection value of the second inertial sensor **302** is in opposite phase to the detection value of the first inertial sensor **301**.

In the embodiment, the first inertial sensor **301** and the second inertial sensor **302** have the same structure. However, structures of the first inertial sensor **301** and the second inertial sensor **302** may also be different from each other.

For example, when the circuit board **15** is warped due to thermal expansion of the circuit board **15** or due to an external force, a stress from the circuit board **15** is applied to members disposed on the first surface **15***f* and the second surface **15***r*. Stresses are applied to the first surface **15***f* and the second surface **15***r* from mutually opposite directions. For example, when a compressive stress is applied to a member disposed on the first surface **15***f*, a tensile stress is applied to a member disposed on the second surface **15***r*. The stress from the circuit board **15** distorts the sensor element **200** and the like accommodated in the package **310** via the package **310**, so that detection accuracy of the inertial sensor **300** is reduced.

In the embodiment, as described above, the first inertial sensor **301** and the second inertial sensor **302** are disposed on the first surface **15***f* of the circuit board **15**. That is, the first inertial sensor **301** and the second inertial sensor **302** are disposed on one surface of the circuit board **15**. The expression "disposed on one surface of the circuit board **15**" means that the components are disposed on the same surface of the circuit board **15**.

By disposing the first inertial sensor **301** and the second inertial sensor **302** on the one surface of the circuit board **15**, the stress from the circuit board **15** is generated from the same direction (direction orthogonal to the detection axis) in the first inertial sensor **301** and the second inertial sensor **302**. For example, when a compressive stress from the circuit board **15** is applied to the first inertial sensor **301**, the compressive stress from the circuit board **15** is also applied to the second inertial sensor **302**. That is, noises caused by the stress from the circuit board **15** are in-phase error factors. Therefore, by generating the differential signal which is the difference between the output signal of the first inertial sensor **301** and the output signal of the second inertial sensor **302**, it is possible to cancel out the noise caused by the stress from the circuit board **15**. Therefore, accuracy of an acceleration measurement value output from the inertial measurement device **100** is improved.

Although the first inertial sensor **301** and the second inertial sensor **302** are disposed on the first surface **15***f* in the embodiment, the first inertial sensor **301** and the second inertial sensor **302** may be disposed on the second surface **15***r*.

In addition, as described above, the first inertial sensor **301** and the second inertial sensor **302** are mounted upright on the first surface **15***f* of the circuit board **15**. Accordingly, a mounting region in which the first inertial sensor **301** and the second inertial sensor **302** are mounted is reduced as compared with a case where a bottom surface of the package **310** faces the first surface **15***f* of the circuit board **15** and the inertial sensor **300** is mounted horizontally on the circuit board **15** (horizontal mounting). Therefore, the noise caused by the stress from the circuit board **15** can be reduced, and the accuracy of the acceleration measurement value output from the inertial measurement device **100** is improved.

In addition, as described above, the C-axis which is the detection axis of the first inertial sensor **301** and the second inertial sensor **302** is the direction along the first surface **15***f* of the circuit board **15**. When the Z direction which is a normal direction of the first surface **15***f* is along a gravity direction and the inertial measurement device **100** is in a stationary state, detection signals of the first inertial sensor **301** and the second inertial sensor **302** are in a state in which an acceleration is zero, that is, are signals corresponding to an origin. However, in general, an acceleration sensor such as the inertial sensor **300** may cause so-called origin drift during which a position of the origin moves.

As described above, in the embodiment, the differential signal which is the difference between the output signal of the first inertial sensor **301** and the output signal of the second inertial sensor **302** is generated. Origin drifts in the detection signals of the first inertial sensor **301** and the second inertial sensor **302** are canceled out by generating the differential signal when the origin drifts are in-phase error factors. Therefore, an origin drift of the acceleration measurement value output from the inertial measurement device **100** is reduced, and origin stability is improved. In this way, since a measurement value with high origin stability is obtained, the inertial measurement device **100** can be suitably used, for example, as an inclination sensor.

In the embodiment, the inertial measurement device **100** measures an acceleration in the Y-axis direction. However, the physical quantity measured by the inertial measurement device **100** is not limited thereto. For example, the inertial measurement device **100** may measure an acceleration in the X-axis direction or the Z-axis direction. Specifically, the acceleration in the X-axis direction can be measured by mounting the inertial sensor **300** upright on the first surface such that the C-axis of the inertial sensor **300** coincides with the X-axis direction. In addition, the acceleration in the Z-axis direction can be measured by mounting the inertial sensor **300** horizontally on the first surface **15***f* such that the C-axis of the inertial sensor **300** coincides with the Z-axis direction. In addition, by combining these mounting manners, for example, the inertial measurement device **100** may measure an acceleration in two axial directions along the X-axis and the Y-axis or may measure an acceleration in three axial directions along the X-axis, the Y-axis, and the Z-axis.

The disposition of the inertial sensor **300** has been described above. Next, a functional configuration of the inertial measurement device **100** will be described with reference to FIG. **8**. FIG. **8** shows a configuration example of a measurement system **400** including the inertial measurement device **100**. As shown in FIG. **8**, the measurement system **400** includes the inertial measurement device **100** and a control device **410**.

The inertial measurement device **100** is fixed to an attachment target body (not shown) and measures a physical quantity occurring on an attachment target body. In the embodiment, the inertial measurement device **100** measures an acceleration as the physical quantity. In addition, the inertial measurement device **100** may measure an inclination of the attachment target body. The control device **410** controls the inertial measurement device **100** and performs processing based on an output signal of the inertial measurement device **100**. The control device **410** is, for example, a computer. The control device **410** may include general hardware as a computer such as a processing device, a storage device, an input and output device, and a display device, all of which are not shown. The control device **410** and the inertial measurement device **100** are communicably connected to each other.

The inertial measurement device **100** includes the first inertial sensor **301**, the second inertial sensor **302**, two analog front ends (AFE) **421** and **422**, the processing circuit **18**, the storage circuit **19**, and a communication unit **423**. The communication unit **423** establishes a communication link with the control device **410** and includes a communication circuit that processes a signal transmitted through the communication link. The communication link may be wired or wireless.

The first inertial sensor **301** detects an acceleration on the first detection axis H**1** and sequentially outputs an output signal corresponding to a detection value thereof to the AFE **421**. The AFE **421** sequentially outputs a digital signal corresponding to the output of the first inertial sensor **301** by performing amplification processing, A/D conversion processing, or the like on the output signal of the first inertial sensor **301**. The second inertial sensor **302** detects an acceleration on the second detection axis H**2** and sequentially outputs an output signal corresponding to a detection value thereof to the AFE **422**. The AFE **422** sequentially outputs a digital signal corresponding to the output of the second inertial sensor **302** by performing amplification processing, A/D conversion processing, or the like on the output signal of the second inertial sensor **302**.

In the embodiment, time-series data of an output signal of the AFE **421** is referred to as measurement data D**1** of the first inertial sensor **301**. Time-series data of an output signal of the AFE **422** is referred to as measurement data D**2** of the second inertial sensor **302**.

The processing circuit **18** sequentially receives the digital signals output from the AFEs **421** and **422**. The processing circuit **18** executes a signal processing program **425** stored in the storage circuit **19** so as to perform various types of calculation processing on the digital signals input from the AFEs **421** and **422**. In addition, the processing circuit **18** performs processing of controlling the first inertial sensor **301** and the second inertial sensor **302** to detect an acceleration, processing of controlling the communication unit **423** to perform data communication with the control device **410**, and the like.

By executing the signal processing program **425**, the processing circuit **18** functions as a measurement data acquisition circuit **431**, a physical quantity calculation circuit **432**, an amplitude calculation circuit **433**, an amplitude ratio calculation circuit **434**, and a sensitivity ratio comparison circuit **435**. That is, the processing circuit **18** includes the measurement data acquisition circuit **431**, the physical quantity calculation circuit **432**, the amplitude calculation circuit **433**, the amplitude ratio calculation circuit **434**, and the sensitivity ratio comparison circuit **435**. At least a part of the functions may be implemented by a logic device.

The measurement data acquisition circuit **431** acquires the measurement data D**1** and D**2** of the first inertial sensor **301** and the second inertial sensor **302**, respectively. Specifically, the measurement data acquisition circuit **431** sequentially acquires the digital signals output from the AFEs **421** and **422**.

The physical quantity calculation circuit **432** calculates the physical quantity based on the measurement data D**1** of the first inertial sensor **301** and the measurement data D**2** of the second inertial sensor **302**. The physical quantity calculation circuit **432** can transmit a calculation value of the physical quantity calculated based on the measurement data D**1** of the first inertial sensor **301** and the measurement data D**2** of the second inertial sensor **302** to the control device **410** as a measurement value of the physical quantity measured by the inertial measurement device **100**.

Specifically, the physical quantity calculation circuit **432** calculates a differential value that is a difference between the measurement data D**1** of the first inertial sensor **301** and the measurement data D**2** of the second inertial sensor **302** at a certain time. Then, the physical quantity calculation circuit **432** converts the differential value into the physical quantity. For example, information defining a correspondence relationship between the differential value and the physical quantity is stored in the storage circuit **19**, and the physical quantity calculation circuit **432** can convert the differential value into the physical quantity based on the information. The information is, for example, a reference table or a relational equation that defines the correspondence relationship between the differential value and the physical quantity. Before conversion into the physical quantity, filter processing for reducing noise or the like may be performed on the measurement data D**1** and D**2** or the differential value. In addition, temperature correction may be performed on the measurement data D**1** and D**2** or the differential value based on temperature characteristics of the first inertial sensor **301** and the second inertial sensor **302**.

The amplitude calculation circuit **433** calculates an amplitude A**1** of the measurement data D**1** of the first inertial sensor **301** and an amplitude A**2** of the measurement data D**2** of the second inertial sensor **302** at a certain time.

Here, the amplitude A**1** of the measurement data D**1** of the first inertial sensor **301** and the amplitude A**2** of the measurement data D**2** of the second inertial sensor **302** at a certain time will be described with reference to FIGS. **9**A and **9**B.

A waveform diagram shown in FIG. **9**A is an example of a waveform of the measurement data D**1**. A waveform diagram shown in FIG. **9**B is an example of a waveform of the measurement data D**2**. As shown in FIGS. **9**A and **9**B, the measurement data D**1** and the measurement data D**2** are opposite phases of each other. The expression "be opposite phases of each other" includes a case where the measurement data D**1** and the measurement data D**2** are not exactly opposite phases due to a difference in characteristics of the first inertial sensor **301** and the second inertial sensor **302**, for example, a difference in temperature characteristics, or due to noises.

In the embodiment, a peak-to-peak value is calculated for each of the amplitudes A**1** and A**2**. The peak-to-peak value is a value showing a difference between a positive maximum value and a negative maximum value in a certain time interval. The amplitudes A**1** and A**2** of the measurement data D**1** and the measurement data D**2** are not limited to peak-to-peak values and may be calculated based on, for example, a standard deviation, or a root mean square value. In FIGS. **9**A and **9**B, the amplitudes A**1** and A**2** in a time interval from 0.4 seconds to 0.6 seconds are shown as examples of the amplitudes A**1** and A**2** of the measurement data D**1** and the measurement data D**2**, respectively.

Referring back to FIG. **8**, description of the inertial measurement device **100** will be continued. The amplitude ratio calculation circuit **434** calculates an amplitude ratio A**1**/A**2** which is a ratio of the amplitude A**1** of the measurement data D**1** to the amplitude A**2** of the measurement data D**2**.

Here, the amplitude ratio A**1**/A**2** of the amplitude A**1** of the measurement data D**1** to the amplitude A**2** of the measurement data D**2** when an abnormality occurs in the first inertial sensor **301** or the second inertial sensor **302** will be described. When an abnormality during which sensitivity changes occurs in the inertial measurement device **100**, the sensitivity of the inertial sensor **300** generally decreases. Therefore, an amplitude of measurement data of the inertial sensor **300** in which the abnormality occurs decreases as the sensitivity decreases.

For example, when an abnormality occurs in the first inertial sensor **301** among the first inertial sensor **301** and the second inertial sensor **302**, sensitivity of the first inertial sensor **301** decreases. Accordingly, the amplitude A**1** of the measurement data D**1** of the first inertial sensor **301** in which the abnormality occurs is smaller than that in a normal state. Therefore, when the abnormality occurs in the first inertial sensor **301**, the amplitude ratio A**1**/A**2** is smaller than that when the first inertial sensor **301** is normal. In addition, when an abnormality occurs in the second inertial sensor **302**, sensitivity of the second inertial sensor **302** decreases. Accordingly, the amplitude A**2** of the measurement data D**2** of the second inertial sensor **302** in which the abnormality occurs is smaller than that in a normal state. Therefore, when the abnormality occurs in the second inertial sensor **302**, the amplitude ratio A**1**/A**2** is larger than that in the normal state.

In this way, when the abnormality occurs in the inertial measurement device **100**, the amplitude ratio A**1**/A**2** changes.

Therefore, self-diagnosis of the inertial measurement device **100** can be performed based on the amplitude ratio A**1**/A**2**.

The sensitivity ratio comparison circuit **435** acquires an initial sensitivity ratio R**1** stored in advance in the storage circuit **19** from the storage circuit **19** and compares the amplitude ratio A**1**/A**2** of the amplitude A**1** of the measurement data D**1** to the amplitude A**2** of the measurement data D**2** with the initial sensitivity ratio R**1**. Then, the sensitivity ratio comparison circuit **435** performs the self-diagnosis of the inertial measurement device **100** based on a comparison result between the amplitude ratio A**1**/A**2** and the initial sensitivity ratio R**1**.

The initial sensitivity ratio R**1** is a ratio of the sensitivity of the first inertial sensor **301** to the sensitivity of the second inertial sensor **302** when the first inertial sensor **301** and the second inertial sensor **302** are normal. In other words, the initial sensitivity ratio R**1** corresponds to a ratio of the amplitude A**1** of the measurement data D**1** of the first inertial sensor **301** to the amplitude A**2** of the measurement data D**2** of the second inertial sensor **302** when the first inertial sensor **301** and the second inertial sensor **302** are normal. The initial sensitivity ratio R**1** is also referred to as a sensitivity ratio R**1**.

An example of a procedure for calculating the initial sensitivity ratio R**1** will be described. First, the amplitude A**1** of the measurement data D1 when a predetermined acceleration occurs on the first detection axis H1 of the first inertial sensor **301** and the amplitude A2 of the measurement data D2 when the predetermined acceleration occurs on the second detection axis H2 of the second inertial sensor **302** are measured. The predetermined acceleration is, for example, a gravitational acceleration.

Next, the initial sensitivity ratio R1 is calculated based on the amplitude A1 when the predetermined acceleration occurs on the first detection axis H1 and the amplitude A2 when the predetermined acceleration occurs on the second detection axis H2. The initial sensitivity ratio R1 is (the amplitude A1 when the predetermined acceleration occurs on the first detection axis H1)/(the amplitude A2 when the predetermined acceleration occurs on the second detection axis H2).

Measurement of the amplitude A1 when the predetermined acceleration occurs on the first detection axis H1 and the amplitude A2 when the predetermined acceleration occurs on the second detection axis H2 is performed when the first inertial sensor **301** and the second inertial sensor **302** are normal. As the normal state, for example, a state in which output characteristics of the first inertial sensor **301** and the second inertial sensor **302** are confirmed to be within a predetermined range can be adopted. The measurement of the amplitude A1 when the predetermined acceleration occurs on the first detection axis H1 and the amplitude A2 when the predetermined acceleration occurs on the second detection axis H2 is performed, for example, at the time of shipping the inertial measurement device **100**, that is, before shipment.

As described above, the initial sensitivity ratio R1 corresponds to the amplitude ratio A1/A2 when the first inertial sensor **301** and the second inertial sensor **302** are normal. Therefore, by comparing the amplitude ratio A1/A2 with the initial sensitivity ratio R1, the self-diagnosis of the inertial measurement device **100** can be performed.

Hereinafter, processing of comparing the amplitude ratio A1/A2 with the initial sensitivity ratio R1 will be described in detail. In the embodiment, the sensitivity ratio comparison circuit **435** performs the self-diagnosis of the inertial measurement device **100** based on whether the amplitude ratio A1/A2 is within a reference range including the initial sensitivity ratio R1.

The reference range is determined as a range which a value of the amplitude ratio A1/A2 is to be within when the first inertial sensor **301** and the second inertial sensor **302** are normal. When the amplitude ratio A1/A2 is compared with the reference range and the amplitude ratio A1/A2 is within the reference range, the sensitivity ratio comparison circuit **435** determines that the inertial measurement device **100** is normal. When the amplitude ratio A1/A2 is compared with the reference range and the amplitude ratio A1/A2 is not within the reference range, the sensitivity ratio comparison circuit **435** determines that the inertial measurement device **100** is abnormal.

In the embodiment, the reference range is defined by the initial sensitivity ratio R1 and a threshold value TH1. The threshold value TH1 is stored in advance in the storage circuit **19** as a value for defining a width of the reference range. That is, the storage circuit **19** stores the initial sensitivity ratio R1 and the threshold value TH1 as the reference range. Instead of the initial sensitivity ratio R1 and the threshold value TH1, only an upper limit value and a lower limit value may be stored. The reference range may be changed to any suitable range as long as the range includes the initial sensitivity ratio R1.

For example, an upper limit of the reference range is (initial sensitivity ratio R1+threshold value TH1), and a lower limit of the reference range is (initial sensitivity ratio R1−threshold value TH1). The threshold value TH1 is positive. That is, "within the reference range" in the embodiment is smaller than (initial sensitivity ratio R1+threshold value TH1) and larger than (initial sensitivity ratio R1−threshold value TH1).

When the amplitude ratio A1/A2 is within the reference range, an absolute value of a difference between the amplitude ratio A1/A2 and the initial sensitivity ratio R1 is smaller than the threshold value TH1. When the amplitude ratio A1/A2 is not within the reference range, the absolute value of the difference between the amplitude ratio A1/A2 and the initial sensitivity ratio R1 is equal to or larger than the threshold value TH1. That is, whether the amplitude ratio A1/A2 is within the reference range defined by the initial sensitivity ratio R1 and the threshold value TH1 can be determined by comparing the absolute value of the difference between the amplitude ratio A1/A2 and the initial sensitivity ratio R1 with the threshold value TH1.

In the embodiment, in order to compare the amplitude ratio A1/A2 with the initial sensitivity ratio R1, the sensitivity ratio comparison circuit **435** first calculates the absolute value of the difference between the amplitude ratio A1/A2 and the initial sensitivity ratio R1. Next, the sensitivity ratio comparison circuit **435** acquires the threshold value TH1 stored in the storage circuit **19** from the storage circuit **19** and compares the absolute value of the difference between the amplitude ratio A1/A2 and the initial sensitivity ratio R1 with the threshold value TH1.

Although "within the reference range" does not include a value that is a boundary of the range in the embodiment, a value that is a boundary of the range may also be included. That is, the sensitivity ratio comparison circuit **435** may determine that the inertial measurement device **100** is normal when the absolute value of the difference between the amplitude ratio A1/A2 and the initial sensitivity ratio R1 is equal to the threshold value TH1.

The processing of comparing the amplitude ratio A1/A2 with the initial sensitivity ratio R1 has been described in detail. As described above, the self-diagnosis of the inertial measurement device **100** can be performed by comparing the amplitude ratio A1/A2 with the initial sensitivity ratio R1.

In the embodiment, the amplitude ratio A1/A2 compared with the initial sensitivity ratio R1 is calculated based on the acceleration occurring on the inertial measurement device **100**, that is, the acceleration occurring on the attachment target body to which the inertial measurement device **100** is attached. That is, in the embodiment, it is possible to perform the self-diagnosis of the inertial measurement device **100** by using the acceleration occurring on the attachment target body. The acceleration occurring on the attachment target body includes, for example, an acceleration that occurs due to environmental vibration, natural vibration, or spontaneous vibration of the attachment target body.

In this way, since the self-diagnosis of the inertial measurement device **100** is performed by using the acceleration occurring on the attachment target body, it is not necessary to provide any self-diagnosis electrode and any configuration necessary for excitation of the self-diagnosis electrode. Therefore, it is possible to prevent a decrease in accuracy of self-diagnosis caused by redundancy.

In addition, in the embodiment, when the self-diagnosis of the inertial measurement device **100** is performed, it is not necessary to stop the measurement of the acceleration performed by the inertial measurement device **100**. Therefore, downtime of the inertial measurement device **100** can be reduced.

The inertial measurement device **100** has been described above. Next, a self-diagnosis method of the inertial measurement device **100** according to the first embodiment will be described with reference to FIG. **10**. Steps S**1** to S**8** shown in FIG. **10** are performed by the processing circuit **18** executing the signal processing program **425**.

When a self-diagnosis command for starting the self-diagnosis of the inertial measurement device **100** is input to the inertial measurement device **100**, the self-diagnosis of the inertial measurement device **100** is started. In the embodiment, the self-diagnosis command is transmitted from the control device **410** shown in FIG. **8** to the inertial measurement device **100**. However, the self-diagnosis command is not limited to being from the control device **410** and may be input to the inertial measurement device **100** by, for example, operating a button (not shown) provided on the inertial measurement device **100**, or may be periodically input to the inertial measurement device **100** by a timer (not shown) provided in the inertial measurement device **100**.

In step S**1**, the measurement data acquisition circuit **431** acquires the measurement data D**1** of the first inertial sensor **301** and the measurement data D**2** of the second inertial sensor **302**.

In step S**2**, the amplitude calculation circuit **433** calculates the amplitude A**1** of the measurement data D**1** of the first inertial sensor **301**. In step S**3**, the amplitude calculation circuit **433** calculates the amplitude A**2** of the measurement data D**2** of the second inertial sensor **302**. As described above, in the embodiment, the amplitude calculation circuit **433** calculates the peak-to-peak values of the amplitudes A**1** and A**2** of the measurement data D**1** and the measurement data D**2**.

In step S**4**, the amplitude ratio calculation circuit **434** calculates the amplitude ratio A**1**/A**2**. Specifically, the amplitude ratio calculation circuit **434** calculates the amplitude ratio A**1**/A**2** which is a ratio of the amplitude A**1** calculated in step S**2** to the amplitude A**2** calculated in step S**3**.

In step S**5**, the sensitivity ratio comparison circuit **435** acquires, from the storage circuit **19**, the initial sensitivity ratio R**1** and the threshold value TH**1** as the reference range.

In step S**6**, the sensitivity ratio comparison circuit **435** determines whether the amplitude ratio A**1**/A**2** is within the reference range defined by the initial sensitivity ratio R**1** and the threshold value TH**1**. For example, the sensitivity ratio comparison circuit **435** first calculates the absolute value of the difference between the amplitude ratio A**1**/A**2** calculated in step S**4** and the threshold value TH**1** acquired in step S**5**. Next, the sensitivity ratio comparison circuit **435** compares the absolute value of the difference between the amplitude ratio A**1**/A**2** and the initial sensitivity ratio R**1** with the threshold value TH**1**.

When the absolute value of the difference between the amplitude ratio A**1**/A**2** and the initial sensitivity ratio R**1** is smaller than the threshold value TH**1**, the sensitivity ratio comparison circuit **435** determines that the amplitude ratio A**1**/A**2** is within the reference range. When the absolute value of the difference between the amplitude ratio A**1**/A**2** and the initial sensitivity ratio R**1** is larger than the threshold value TH**1**, or when the absolute value of the difference between the amplitude ratio A**1**/A**2** and the initial sensitivity ratio R**1** is equal to the threshold value TH**1**, the sensitivity ratio comparison circuit **435** determines that the amplitude ratio A**1**/A**2** is not within the reference range. The sensitivity ratio comparison circuit **435** advances the processing to step S**7** when it is determined that the amplitude ratio A**1**/A**2** is within the reference range, and advances the processing to step S**8** when it is determined that the amplitude ratio A**1**/A**2** is not within the reference range.

In step S**7**, the sensitivity ratio comparison circuit **435** determines that the inertial measurement device **100** is normal, and transmits this self-diagnosis result to the control device **410**. In step S**8**, the sensitivity ratio comparison circuit **435** determines that the inertial measurement device **100** is abnormal, and transmits this self-diagnosis result to the control device **410**. In addition to the self-diagnosis result of the inertial measurement device **100**, the processing circuit **18** may transmit information used for the self-diagnosis of the inertial measurement device **100** to the control device **410**. When step S**7** or step S**8** ends, the processing circuit **18** ends the self-diagnosis method of the inertial measurement device **100**.

The control device **410** may have a function of displaying the self-diagnosis result of the inertial measurement device **100** and the information used for the self-diagnosis of the inertial measurement device **100** on a display device (not shown) provided on the control device **410**. Examples of the information used for the self-diagnosis of the inertial measurement device **100** include the measurement data D**1** and D**2**, the amplitude ratio A**1**/A**2**, the initial sensitivity ratio R**1**, and the threshold value TH**1**.

When the self-diagnosis ends, the inertial measurement device **100** may continue to measure the acceleration. An operation of the inertial measurement device **100** after the end of the self-diagnosis is not limited thereto. For example, the inertial measurement device **100** may stop the measurement of the acceleration after the self-diagnosis during which abnormality is determined ends.

As described above, according to the embodiment, the following effects can be obtained.

The inertial measurement device **100** includes: the first inertial sensor **301** having the first detection axis H**1**; the second inertial sensor **302** having the second detection axis H**2** defined in the direction opposite to the first detection axis H**1**; and the processing circuit **18** configured to execute self-diagnosis based on whether the amplitude ratio A**1**/A**2** that is a ratio of the amplitude A**1** of the output of the first inertial sensor **301** to the amplitude A**2** of the output of the second inertial sensor **302** is within the reference range. Accordingly, it is possible to prevent a decrease in accuracy of self-diagnosis of the inertial measurement device **100**.

In addition, in the self-diagnosis method of the inertial measurement device **100** including the first inertial sensor **301** having the first detection axis H**1**, the second inertial sensor **302** having the second detection axis H**2** defined in the direction opposite to the first detection axis H**1**, and the processing circuit **18** configured to acquire an output of the first inertial sensor **301** and an output of the second inertial sensor **302**, the processing circuit **18** executes self-diagnosis based on whether a ratio of the amplitude A**1** of the output of the first inertial sensor **301** to the amplitude A**2** of the output of the second inertial sensor **302** is within the reference range. Accordingly, it is possible to prevent a decrease in accuracy of self-diagnosis of the inertial measurement device **100**.

2. Second Embodiment

Next, the inertial measurement device **100** and a self-diagnosis method of the inertial measurement device **100** according to a second embodiment will be described. The inertial measurement device **100** according to the second embodiment is the same as that of the first embodiment except that an operation of the processing circuit **18** is different when the inertial measurement device **100** is determined to be abnormal. Description of the same configuration as that of the first embodiment will be omitted.

First, the inertial measurement device **100** according to the embodiment will be described. As described above, in general, an amplitude of measurement data of the inertial sensor **300** in which an abnormality occurs decreases. By using this fact, when it is determined that the inertial measurement device **100** is abnormal, it is possible to specify a normal inertial sensor among the first inertial sensor **301** and the second inertial sensor **302**.

In the embodiment, when an abnormality is determined as a result of self-diagnosis, the inertial measurement device **100** specifies a normal inertial sensor among the first inertial sensor **301** and the second inertial sensor **302** by comparing the amplitude **A1** with the amplitude **A2**. For example, when the amplitude **A1** is larger than the amplitude **A2**, the first inertial sensor **301** is less likely to be abnormal than the second inertial sensor **302**. That is, when a self-diagnosis result is abnormal and the amplitude **A1** is larger than the amplitude **A2**, the first inertial sensor **301** can be specified as a normal inertial sensor, and the second inertial sensor **302** can be specified as an abnormal inertial sensor.

When it is determined that the inertial measurement device **100** is abnormal, the processing circuit **18** transmits a calculated value of a physical quantity calculated based on measurement data of the normal inertial sensor among the first inertial sensor **301** and the second inertial sensor **302** to the control device **410** as a measurement value of the physical quantity measured by the inertial measurement device **100**.

As compared with a calculated value of the physical quantity calculated based on a differential value between measurement data of the abnormal inertial sensor and measurement data of the normal inertial sensor, the calculated value of the physical quantity calculated based on the measurement data of the normal inertial sensor has higher reliability when used as the measurement value of the inertial measurement device **100**. Therefore, when it is determined that the inertial measurement device **100** is abnormal, the calculated value of the physical quantity calculated based on the measurement data of the normal inertial sensor is used as the measurement value of the physical quantity measured by the inertial measurement device **100**, so that a certain level of reliability can be ensured for the measured value of the inertial measurement device **100**. Accordingly, when it is determined that the inertial measurement device **100** is abnormal, the inertial measurement device **100** can continue the measurement while outputting the measurement value for which a certain level of reliability is ensured.

The amplitude ratio calculation circuit **434** compares the amplitude **A1** of the measurement data **D1** with the amplitude **A2** of the measurement data **D2** and outputs, to the storage circuit **19**, sensor selection information that is information indicating the normal inertial sensor among the first inertial sensor **301** and the second inertial sensor **302**. Specifically, when the amplitude **A1** is larger than the amplitude **A2**, the sensor selection information is information indicating the first inertial sensor **301**, and when the amplitude **A2** is larger than the amplitude **A1**, the sensor selection information is information indicating the second inertial sensor **302**. The storage circuit **19** stores the sensor selection information output from the amplitude ratio calculation circuit **434**.

When it is determined that the inertial measurement device **100** is normal as a result of the self-diagnosis of the inertial measurement device **100**, the physical quantity calculation circuit **432** operates in the same manner as in the first embodiment. That is, the physical quantity calculation circuit **432** calculates the physical quantity based on the measurement data D1 of the first inertial sensor **301** and the measurement data D2 of the second inertial sensor **302**. On the other hand, when it is determined that the inertial measurement device **100** is abnormal as the result of the self-diagnosis of the inertial measurement device **100**, the physical quantity calculation circuit **432** calculates the physical quantity based on the measurement data of the normal inertial sensor among the first inertial sensor **301** and the second inertial sensor **302**.

When it is determined that the inertial measurement device **100** is abnormal, first, the physical quantity calculation circuit **432** acquires the sensor selection information stored in the storage circuit **19** from the storage circuit **19**. Next, the physical quantity calculation circuit **432** acquires measurement data of an inertial sensor indicated by the sensor selection information among the measurement data D1 of the first inertial sensor **301** and the measurement data D2 of the second inertial sensor **302**. The physical quantity calculation circuit **432** calculates the physical quantity based on the acquired measurement data. Next, the physical quantity calculation circuit **432** transmits a calculated value of the calculated physical quantity to the control device **410** as the measurement value of the physical quantity measured by the inertial measurement device **100**.

In this way, in the embodiment, when the amplitude ratio **A1**/**A2** is not within the reference range, the processing circuit **18** adopts an output of an inertial sensor that outputs a larger amplitude among the first inertial sensor **301** and the second inertial sensor **302** as an output of the inertial measurement device **100**. Specifically, when the amplitude ratio **A1**/**A2** is not within the reference range, the processing circuit **18** adopts, as the measurement value of the physical quantity of the inertial measurement device **100**, the calculated value of the physical quantity calculated based on the measurement data of the inertial sensor that outputs the larger amplitude among the first inertial sensor **301** and the second inertial sensor **302**. Accordingly, when it is determined that the inertial measurement device **100** is abnormal, the inertial measurement device **100** can continue measurement by outputting the measurement value for which a certain level of reliability is ensured.

3. Third Embodiment

Next, the inertial measurement device **100** and a self-diagnosis method of the inertial measurement device **100** according to a third embodiment will be described with reference to FIG. **11**. The inertial measurement device **100** according to the third embodiment is the same as that of the first embodiment except that a vibration generator **500** is provided. The same components as those in the first embodiment are denoted by the same reference numerals, and description thereof will be omitted.

First, the inertial measurement device **100** according to the embodiment will be described. As shown in FIG. **11**, in addition to the first inertial sensor **301**, the second inertial sensor **302**, the processing circuit **18**, and the storage circuit **19**, the vibration generator **500** serving as an actuator is further disposed on the first surface **15***f* of the circuit board **15** provided in the inertial measurement device **100** according to the embodiment.

The vibration generator **500** is electrically coupled to the processing circuit **18** via a wiring (not shown) or the like provided on the circuit board **15**. In the embodiment, the vibration generator **500** is disposed in the vicinity of the first inertial sensor **301** and the second inertial sensor **302**. The vibration generator **500** is disposed at equal distances from the first inertial sensor **301** and the second inertial sensor **302** in the plan view. However, disposition of the vibration generator **500** is not particularly limited. For example, the vibration generator **500** may be disposed on the second surface **15***r* of the circuit board **15** or may be disposed in the container **1** shown in FIG. **3**.

When the vibration generator **500** is driven by a drive signal output from the processing circuit **18**, the vibration generator **500** vibrates. The vibration generator **500** generates a motion including a component of the first detection axis H**1** by vibration. In the embodiment, the component of the first detection axis H**1** means a Y-axis component.

Since the vibration generator **500** generates the motion including the component of the first detection axis H**1**, an acceleration in the direction along the first detection axis H**1** occurs on the inertial measurement device **100**. Accordingly, the first inertial sensor **301** detects the acceleration on the first detection axis H**1**. The second inertial sensor **302** detects the acceleration on the second detection axis H**2** defined in the direction opposite to the first detection axis H**1**.

In the inertial measurement device **100** disposed in a static environment such that the Z direction is along a gravity direction, the amplitude A**1** of the measurement data D**1** of the first inertial sensor **301** and the amplitude A**2** of the measurement data D**2** of the second inertial sensor **302** are zero if variations in the measurement data D**1** and D**2** caused by noises or the like are ignored. In this case, self-diagnosis of the inertial measurement device **100** cannot be performed based on the amplitude ratio A**1**/A**2**. The expression "acceleration is zero" refers to, in addition to a case where no acceleration substantially occurs, a case where, even if an acceleration in the direction along the first detection axis H**1** occurs, the acceleration is less than a detection lower limit of the first inertial sensor **301** and the second inertial sensor **302**.

In the embodiment, since the first inertial sensor **301** and the second inertial sensor **302** detect the acceleration in the direction along the first detection axis H**1** occurring due to the motion of the vibration generator **500**, the processing circuit **18** can perform the self-diagnosis of the inertial measurement device **100** based on the amplitude ratio A**1**/A**2** even in a static environment. In other words, the processing circuit **18** executes the self-diagnosis of the inertial measurement device **100** by calculating the amplitude ratio A**1**/A**2** based on the motion including the component of the first detection axis H**1** generated by the vibration generator **500** that serves as an actuator. Accordingly, the processing circuit **18** can perform the self-diagnosis of the inertial measurement device **100** even in a static environment.

The vibration generator **500** is not particularly limited as long as the vibration generator **500** is a device that generates vibration. For example, various actuators such as an eccentric rotation mass type vibration motor, a voice coil type vibration motor, a vibration cylinder that drives a piston by hydraulic pressure or air pressure, and a piezoelectric motor can be used as the vibration generator **500**.

In the embodiment, an eccentric rotation type disc-shaped vibration motor is used as the vibration generator **500**. The vibration motor includes a rotation shaft (not shown) and an eccentric weight (not shown) attached to the rotation shaft. The rotation shaft of the vibration motor is disposed in a direction along the Z-axis direction which is the normal direction of the first surface **15***f* of the circuit board **15**. The eccentric weight of the vibration motor rotates about the rotation shaft along the Z-axis. Accordingly, the vibration motor moves in a direction along the first surface **15***f* of the circuit board **15**. That is, the vibration motor generates a motion including an X-axis component and a Y-axis component (the component of the first detection axis H**1**).

The processing circuit **18** may drive the vibration generator **500** as necessary. For example, whether the inertial measurement device **100** is in a static environment may be determined, and whether to drive the vibration generator **500** may be selected according to a determination result thereof. Specifically, the processing circuit **18** may drive the vibration generator **500** when the processing circuit **18** determines that the inertial measurement device **100** is in a static environment, and may not drive the vibration generator **500** when it is determined that the inertial measurement device **100** is not in a static environment.

An example of an operation by which the processing circuit **18** determines whether the inertial measurement device **100** is in a static environment will be described. For example, the processing circuit **18** can determine whether the inertial measurement device **100** is in a static environment by comparing a magnitude of the amplitude A**1** of the measurement data D**1** and a magnitude of the amplitude A**2** of the measurement data D**2** with a predetermined reference value stored in the storage circuit **19**. The processing circuit **18** acquires the reference value from the storage circuit **19** and compares the reference value with the amplitude A**1** and the amplitude A**2**. When both the amplitude A**1** and the amplitude A**2** are smaller than the reference value, the processing circuit **18** determines that the inertial measurement device **100** is in a static environment. When at least one of the amplitude A**1** and the amplitude A**2** is larger than the reference value, the processing circuit **18** determines that the inertial measurement device **100** is not in a static environment.

According to the embodiment, the following effects can be obtained in addition to the effects in the first embodiment. The inertial measurement device **100** further includes the vibration generator **500** that serves as an actuator, the vibration generator **500** generates the motion including the component of the first detection axis H**1**, and the processing circuit **18** executes the self-diagnosis of the inertial measurement device **100** based on the motion including the component of the first detection axis H**1** generated by the vibration generator **500**. Accordingly, for example, in a static environment, the processing circuit **18** can still perform the self-diagnosis of the inertial measurement device **100**.

The inertial measurement device **100** has been described above based on the first embodiment to the third embodiment. However, the present disclosure is not limited thereto, and the configuration of each unit can be replaced with any configuration having the same function. In addition, any other components may be added to the present disclosure. In addition, the embodiments may be appropriately combined.

What is claimed is:

1. An inertial measurement device comprising:

a first inertial sensor having a first detection axis;

a second inertial sensor having a second detection axis defined in a direction opposite to the first detection axis; and

a processing circuit configured to execute self-diagnosis based on whether a ratio of an amplitude of an output of the first inertial sensor to an amplitude of an output of the second inertial sensor is within a reference range.

2. The inertial measurement device according to claim **1**, wherein,

when the ratio is not within the reference range, the processing circuit adopts, as a device output, an output of one of the first inertial sensor and the second inertial sensor whose amplitude of the output is larger.

3. The inertial measurement device according to claim **1**, further comprising:

an actuator configured to generate a motion including a component of the first detection axis, wherein

the processing circuit executes self-diagnosis based on the motion generated by the actuator.

4. The inertial measurement device according to claim **1**, further comprising:

a storage medium configured to store the reference range.

5. The inertial measurement device according to claim **1**, wherein

the first inertial sensor and the second inertial sensor are disposed on one surface of a board.

6. The inertial measurement device according to claim **1**, wherein

each of the first inertial sensor and the second inertial sensor is a frequency-variable type acceleration sensor.

7. A self-diagnosis method of an inertial measurement device including a first inertial sensor having a first detection axis, a second inertial sensor having a second detection axis defined in a direction opposite to the first detection axis, and a processing circuit configured to acquire an output of the first inertial sensor and an output of the second inertial sensor, wherein

the processing circuit executes self-diagnosis based on whether a ratio of an amplitude of the output of the first inertial sensor to an amplitude of the output of the second inertial sensor is within a reference range.

* * * * *