



(51) International Patent Classification:
B81C 99/00 (2010.01)

(21) International Application Number:
PCT/EP2018/068649

(22) International Filing Date:
10 July 2018 (10.07.2018)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10 2017 115 667.4
12 July 2017 (12.07.2017) DE

(71) Applicant: TDK ELECTRONICS AG [DE/DE]; Rosen-
heimer Str. 141 e, 81671 München (DE).

(72) Inventors: BARBUL, Andreas; Sammstr. 7, 81669
München (DE). PAHL, Wolfgang; Rupert-Mayer-Str. 6,
81379 München (DE).

(74) Agent: EPPING HERMANN FISCHER PATENTAN-
WALTSGESELLSCHAFT MBH; Schloßschmidstr. 5,
80639 München (DE).

(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,
HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP,

KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

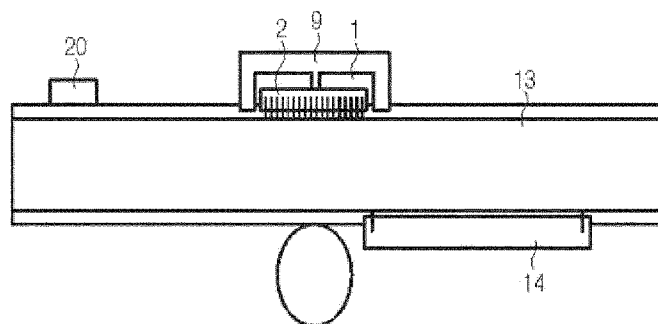
(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

Published:

- with international search report (Art. 21(3))
- before the expiration of the time limit for amending the
claims and to be republished in the event of receipt of
amendments (Rule 48.2(h))

(54) Title: METHOD FOR MEASURING A BEHAVIOUR OF A MEMS DEVICE

Fig. 3



(57) Abstract: The present invention concerns a method for measuring a behaviour of a MEMS device (1) comprising a 6-axis or 9-axis inertial sensor (2), wherein the method comprises the steps of: A. Mounting the MEMS device (1) to a testing apparatus (13) that comprises a vibration source (14), B. Applying a vibration to the MEMS device (1) by the vibration source (14) and, simultaneously, moving the testing apparatus (13) according to a predefined movement pattern, C. Reading output data provided by the inertial sensor (2) and comparing the output data to the predefined movement pattern and/or D. Reading output data provided by the inertial sensor (2) and calculating a frequency response curve of the inertial sensor (2). Moreover, the present invention also concerns an alternative method for measuring the behaviour of a MEMS device.



Description

Method for measuring a behaviour of a MEMS device

5 The present invention relates to a method for measuring a behaviour of a MEMS device comprising an inertial sensor. The behaviour of the MEMS device that is measured by this method may be a mechanical attenuation behaviour in response to a vibration being applied to the MEMS device.

10

It is known that an inertial sensor, for example a gyroscope, may provide unreliable data when a disturbance, e.g. vibration, is applied to the inertial sensor, in particular when the frequency of the disturbance is close to the
15 resonance frequency of the inertial sensor. Due to the ongoing trend for further miniaturization, in most MEMS devices there is almost no space for damping material or structures outside of a MEMS device that may damp a vibration of the device. Thus, sound sources or other external
20 vibration sources may cause a major malfunction of the MEMS device which can be difficult to counter with digital filters or sensor fusion algorithms alone.

For this reason, a MEMS device comprising a damping structure
25 has been developed as disclosed in WO 2017/054868 A1. The damping structure is spring and air-based and requires almost no additional volume. It provides a fast attenuation of a vibration applied to a MEMS device. However, in view of the newly developed MEMS device comprising a damping structure,
30 the need has arisen to measure the performance of the damping structure.

Thus, it is an object of the present invention to provide a method that allows to measure the behaviour of a MEMS device in a response to a vibration being applied to the device. The method is particularly relevant for MEMS devices comprising a damping structure. However, the method can also be performed to evaluate other MEMS devices.

A method for measuring a behaviour of an MEMS device comprising a 6-axis or 9-axis inertial sensor is proposed which comprises the steps of:

- A. Mounting the MEMS device to a testing apparatus that comprises a vibration source,
- B. Applying a vibration to the MEMS device by the vibration source and, simultaneously, moving the testing apparatus according to a predefined movement pattern,
- C. Reading output data provided by the inertial sensor and comparing the output data to the predefined movement pattern.

Additionally or alternatively to step C, the method can further comprise the step D. Reading output data provided by the inertial sensor and calculating a frequency response curve of the inertial sensor.

Accordingly, the method allows to evaluate the accuracy of the data recorded by the inertial sensor when a vibration is applied to the MEMS device. Thus, the method may help to evaluate if an inertial sensor is able to provide reliable data even when a vibration is applied to the MEMS device. The method may also help to evaluate a performance of a damping of the MEMS device.

A 6-axis inertial sensor can comprise a 3-axis gyroscope and a 3-axis accelerometer. Accordingly, the 6-axis inertial sensor can be configured to measure rotations and accelerations into three dimensions.

5

A 9-axis inertial sensor can comprise a 3-axis gyroscope, a 3-axis accelerometer and a 3-axis compass. Thus, the 9-axis inertial sensor can be configured to measure rotations and accelerations into three dimensions and, additionally, to
10 measure an absolute position in three dimensions.

The inertial sensor may be part of an inertial measurement unit (IMU). An inertial measurement unit is an electronic device that measures and reports a body's specific force,
15 angular rate, and sometimes the magnetic field surrounding the body, using a combination of accelerometers and gyroscopes, sometimes also magnetometers. An inertial measurement unit works by detecting linear acceleration using one or more accelerometers and rotational rate using one or
20 more gyroscopes. Some also include a magnetometer which is commonly used as a heading reference. Typical configurations contain one accelerometer, one gyroscope, and magnetometer per axis for each of the three vehicle axes. The three axes are referred to as pitch, roll and yaw. The terms "pitch",
25 "roll" and "yaw" are used in this context as common in flight dynamics which is the science of air-vehicle orientation and control in three dimensions. The angles of rotation in three dimensions about the vehicle's center of mass are known as *roll*, *pitch* and *yaw*. The inertial measurement unit may be
30 configured for inertial measurements with respect to six or nine axes.

The inertial sensor may be any sensor suitable for measuring a linear or rotational movement or a linear or rotational acceleration. For example, the inertial sensor may be a gyroscope. The inertial sensor may comprise multiple sensors.

5

In step A the MEMS device is mounted to the testing apparatus. In this context, mounting may be defined as a temporary fixing. After the measurement has been completed, the MEMS device may be removed from the testing apparatus. In particular, multiple MEMS devices may be mounted to the testing apparatus simultaneously. Further, multiple MEMS devices may be measured simultaneously. Thus, the method is suitable for mass production wherein multiple MEMS devices are tested at the same time.

10

The testing apparatus may be any surface to which the MEMS device can be mounted. For example, the testing apparatus may be a printed circuit board or a measurement table. The testing apparatus may be moveable, in particular tiltable.

15

The testing apparatus may be configured to be tilted with respect to more than one axis.

The vibration source may be a piezoelectric vibration source or an electromagnetic exciter. The vibration source may be configured to apply a continuous or a discontinuous vibration. The vibration source may be configured to apply a vibration with a well-known amplitude and frequency. The vibration source may be configured such that the amplitude and/or the frequency of the vibration can be amended during the measurement.

20

In step B, the MEMS device is moved according to a predefined movement pattern. The movement pattern may comprise a

sequence of defined movements of the testing apparatus. For example, the predefined movement pattern may comprise tilting movements of the testing apparatus. The testing apparatus may be tilted in different directions and with different angular rates.

As the predefined movement pattern is well-known, it is possible, in step C, to compare the movements calculated based on the output data provided by the inertial sensor with the actual movement which is known from the predefined movement pattern. Thus, step C may allow to calculate an error by which the data provided by the inertial sensor deviate from the actual position. Step C may be performed by an evaluation unit outside of the MEMS device.

In step D, a frequency response curve of the inertial sensor is calculated based on output data provided by the inertial sensor. The frequency response curve describes the response of the inertial sensor to vibrations of different frequencies. The frequency response curve may provide information concerning the frequency dependency of deviations of a measurement provided by the inertial sensor from a correct value, wherein the deviation is caused by the vibration.

The method provides the advantage that it can be performed with an encapsulated MEMS device. Thus, no further manufacturing steps are necessary after the measurement of the behaviour. Instead, the measurement can be performed in a last step of a final testing after the manufacturing process is completed.

The method can be performed simultaneously for many MEMS devices. Moreover, the method can be performed very fast. Thus, the method is adapted for a mass production of MEMS devices.

5

The testing apparatus may comprises a 3-axis accelerometer configured to measure a frequency of a vibration applied to the MEMS device, wherein, in step B, the frequency of the applied vibration is varied, and wherein, in step D, the frequency response curve is calculated based on the output data by the inertial sensor (2) and the data provided by the 3-axis accelerometer.

The 3-axis accelerometer may have a resonance frequency which differs from the resonance frequency of a 3-axis gyroscope of the inertial sensor. Thus, the 3-axis accelerometer may not be significantly affected by a vibration having a frequency which corresponds to the resonance frequency of the 3-axis gyroscope.

20

In step C, a software algorithm may determine whether the difference between the output data provided by the inertial sensor and the predefined movement pattern is within a predetermined acceptance limit. Thus, the method allows to check if a MEMS device fulfils a customer requirement regarding robustness against disturbances. The roll angles measured by the inertial sensor should not be affected during tilting of the MEMS device if the MEMS device is working inside the customer requirements. MEMS devices that do not fulfil such requirements may be rejected in a final testing after a manufacture process is completed.

30

According to the predefined movement pattern, the testing apparatus may be tilted at a defined angular rate in different directions during step B, wherein a roll angle and a pitch angle may be calculated based on the output data
5 provided by the inertial sensor in step C. The roll angle and the pitch angle may define the orientation of a rotation axis.

In step C, the output data provided by the inertial sensor
10 may be evaluated using a sensor fusion algorithm comprising a Kalman filter before comparing the output data to the predefined movement pattern. The sensor fusion algorithm may be suitable for removing an error in the measurement of the inertial sensor. The Kalman filter may be a digital Kalman
15 filter. Using a sensor fusion algorithm comprising a Kalman filter may significantly increase the accuracy in the measurement results determined by the inertial sensor. In particular, for vibrations having a rather small amplitude, the sensor fusion algorithm may be able to remove the effect
20 of the vibration almost completely.

The inertial sensor may comprise a gyroscope. Gyroscopes tend to be sensitive to disturbances that appear in a frequency close to the gyroscopes resonance frequency. The gyroscope
25 may have different resonance frequencies with respect to different axes.

The inertial sensor may be resiliently mounted on a carrier by means of a spring element wherein an airgap is provided
30 between a top surface of the carrier and a bottom surface of the inertial sensor, wherein a damping structure is applied to at least one surface chosen from a first surface located on the carrier and a second surface located on the inertial

sensor. Accordingly, a damping of the inertial sensor may be spring and air-based. The spring element may comprise a metal, e.g. copper, or a silicon material. In particular, the MEMS device may comprise a damping structure as disclosed in
5 WO 2017/054868 A1.

The method is particularly suitable for MEMS devices comprising a damping structure as the method may allow to evaluate the quality of the damping. However, it may also be
10 interesting to measure the effect of a vibration applied to a MEMS device which does not comprise a damping structure.

The damping structure may be applied as a layer between the inertial sensor and the carrier on one of the first and
15 second surface, wherein the layer comprises recesses and wherein the recesses are at least measured to accommodate the spring elements. The spring elements may comprise an elongated structure that is linear, bent or angled, a first end of the extended structure being coupled to a first anchor
20 point on the carrier and a second end of the extended structure being coupled to a second anchor point on the sensor system, wherein the height of the airgap normal to the surface is smaller than the distance normal to the surface between first and second anchor point. Thus, the damping
25 structure may be arranged to reduce the width of the airgap.

The inertial sensor may be encapsulated in a sealed package. The method can be performed with an encapsulated MEMS device. No opening in the package is required for performing the
30 measurement of the behaviour. Thus, no further manufacturing steps are necessary after the method has been performed. Instead, the method can be performed after a manufacturing process has been completed.

Multiple MEMS devices can be mounted to the testing apparatus in step A, wherein the behaviour of the multiple MEMS devices is measured simultaneously in steps B and C. The method is suitable for a mass production.

5

The vibration applied in step B may be continuous or discontinuous. When the vibration is applied discontinuously, it can be measured how fast the MEMS device returns to its normal operation mode, i.e. how effective a damping structure can attenuate a vibration of the MEMS device. If the vibration is applied continuously, it can be evaluated if the MEMS device is functional even under vibration. Thus, the tolerance of the device to vibration can be determined.

15 The testing apparatus can be rotated at an angular rate in the range of 0.001 degrees/second to 1000 degrees/second during step B. The rate can be changed during step B.

The vibration source may vibrate with a frequency in the range of 0.1 kHz to 1000 kHz during step B, preferably in the range of 19 to 80 kHz and more particularly in the range of 20 to 35 kHz. This frequency range is typical for the resonance frequency of an inertial sensor. Measurements with a vibration having a frequency close to the resonance frequency of the sensor are particularly relevant. The frequency of the vibration can also be adapted to higher frequencies, like an integer multiple of the resonance frequency of one gyroscope or different gyroscopes in one package so as to reach the range of special harmonics of the MEMS device or multiple devices in one package.

30

The vibration source can vibrate with an amplitude in the range of 1 nm to 10 μ m during step B. The amplitude and the frequency of the vibration may change during step B.

5 The testing apparatus is moved during step B such that the g-rate in the range of 0.01 g to 100 g is applied to the MEMS device. Preferably, the rate is between 0.5 g to 10 g. A g-rate of more than 100 should not be applied as, otherwise, the inertial sensor may be damaged by the g-force. A g-rate
10 below 0.01 should not be applied as it may be difficult to measure such low g-forces with a sufficient accuracy.

The method may be performed to evaluate MEMS devices intended for all kinds of purposes. For example, the MEMS device may
15 be used in consumer products, e.g. a smart cellphone or a civilian drone. In smart cellphones and civilian drones, inertial sensors are used to determine an orientation of the respective device. Smart cellphones often comprise powerful vibration sources, e.g. speakers. Civilian drones may be used
20 in environments with acoustic noise which may result in vibrations of the drone. Thus, for consumer products like cellphones and civilian drones, it is crucial to know if an inertial sensor provides reliable data when a vibration is applied to the consumer product.

25

The MEMS device may also be used in an electronic component used for an automotive application. For example, a gyroscope may be used for movement tracking in an automotive application. Ultrasound haptic feedback may occur in the
30 automotive application which may result in a vibration of the MEMS device.

Inertial sensors, for example gyroscopes, may be used for detecting acoustically caused vibrations, for example speech.

Furthermore, the MEMS device may also be used in a high value device, for example in a rocket, an airplane, a drone for military or aerospace purposes. In such high value devices, it is also important to know how the MEMS device responds to a vibration.

10 According to another aspect, the present invention concerns a method for measuring the behaviour of an MEMS device comprising an inertial sensor, wherein the method comprises the step of applying a vibration to the inertial sensor and measuring the attenuation of the vibration using a laser
15 Doppler vibrometer. The method using the laser Doppler vibrometer is more complicated and is less suitable for mass production than the method according to the first aspect. However, it may provide an improved accuracy. In a mass production of a multitude of MEMS devices, a measurement of
20 the behaviour using a laser Doppler vibrometer may be performed for a control sample comprising only a small number of MEMS devices.

In order to perform this method, it has to be ensured that a
25 laser beam can be applied to the inertial sensor. The MEMS device may comprise a cap which seals the inertial sensor, wherein the cap is transparent for a laser beam used in the laser Doppler vibrometer. Alternatively, the MEMS device may comprise a cap which covers the inertial sensor, wherein the
30 cap has one or more holes, wherein a laser beam is applied to the inertial sensor through one of the holes, wherein the one or more holes are sealed after measuring the attenuation of the vibration.

In the following, the present invention is described in detail with reference to the figures.

Figures 1 and 2 show MEMS devices comprising a damping
5 structure.

Figure 3 shows a setup for performing a measurement of a behaviour of a MEMS device.

10 Figures 4 to 8 show results of different measurements.

Figure 9 shows another method of measuring the behaviour of a MEMS device.

15 The present invention concerns a method for measuring a behaviour of a MEMS device 1 comprising an inertial sensor 2. The behaviour may, in particular, be a mechanical attenuation behaviour in response to a vibration applied to the MEMS device 1. Such a measurement is particularly relevant for a
20 MEMS device 1 which comprises a damping structure 3 configured to attenuate a vibration of the inertial sensor 2. Figures 1 and 2 show such a MEMS device 1.

It is the purpose of the measurement to evaluate the
25 performance of the MEMS device 1 when the MEMS device 1 is subjected to a mechanical disturbance, e.g. a vibration. The measurement is designed to determine if the inertial sensor 2 can provide reliable information even if a vibration is applied to the MEMS device 1. Moreover, the measurement is
30 designed to determine an attenuation of a vibration of the MEMS device 1. For example, the measurement setup is designed to determine how long it takes, after the disappearance of a disturbance in form of a vibration, until the inertial sensor

2 provides reliable data again. Thus, these measurements may allow to evaluate the performance of the damping structure 3 and/or of a sensor fusion algorithm.

5 Figure 1 shows a cross section through the MEMS device 1. The device 1 comprises an inertial measurement unit 4 that comprises the inertial sensor 2. The MEMS device 1 may also comprise a pressure sensor or a microphone. The inertial measurement unit 4 is resiliently mounted onto a carrier 5
10 via spring elements 6. The spring elements 6 may comprise a stand-off 7 on the carrier 5 and a free standing end laterally extending therefrom. The inertial measurement unit 4 is bonded to the free standing end by means of bumps 8. Via the spring element 6, stand-off 7 and bump 8 electrical
15 contact between second electrical contacts P2 on a bottom surface 10 of the inertial measurement unit 4 and first electrical contacts P1 on the carrier 5 is achieved.

The carrier 5 may be a multilayer printed circuited board
20 that may have a multilayer structure comprising at least one wiring layer and other internal wiring connecting the first electrical contacts P1 to external contacts P3 of the MEMS device 1 on a bottom surface of the carrier.

25 A cap 9 is bonded to a top surface 12 of the carrier 5 via a glue or solder. Between cap 9 and carrier 5 a volume is enclosed accommodating at least the inertial measurement unit 4. The volume may be necessary for the function of the MEMS device 1 and may provide protection against chemical and
30 mechanical impact from the environment. For clarity reasons only the inertial measurement unit 4 comprising the inertial sensor 2 is shown. But other components of the MEMS device 1

like an ASIC for example may be accommodated too under the cap 9.

An external shock may be able to induce a resonance of the inertial measurement unit 4. This resonance may saturate the inertial sensor 2 and disturb its sensing function. In order to prevent such a disturbance, the MEMS device 1 comprises a damping structure 3. In the embodiment shown in Figure 1, the damping structure 3 is applied to the bottom surface 10 of the inertial measurement unit 4. The damping structure 3 comprises recesses to accommodate the spring elements 6. Thereby the airgap 11 between the bottom surface 10 of the inertial measurement unit 4 and the top surface 12 of the carrier 5 is reduced. As the spring elements 6 are mounted to an anchor point on the bottom surface 10 of the inertial measurement unit 4 "below" the damping structure 3 the maximum mutual movement of inertial measurement unit 4 versus carrier 5 is limited by the air gap 11 between top surface 12 of carrier 5 and a bottom surface of the damping structure 3. The air gap 11 is reduced with regard to a device which does not comprise a damping structure 3. The height of the air gap 11 is set to a value small enough that squeeze film damping occurs.

Figure 2 shows a cross section of a MEMS device 1 according to a second embodiment of the invention. Different from the first embodiment of figure 1, the damping structure 3 is applied to the top surface 12 of the carrier 5. The thus reduced air gap 11 is formed between a top surface on the damping structure 3 and the bottom surface 10 of the inertial measurement unit 4. The same effect is achieved by this embodiment as the same squeeze film damping occurs at this air gap 11.

Figure 3 shows a measurement setup which enables a measuring of the mechanical attenuation behaviour of a MEMS device 1. The measurement setup comprises a testing apparatus 13. The testing apparatus 13 may be a measurement table or a printed
5 circuit board.

The MEMS device 1 is mounted to surface of the testing apparatus 13, for example to a top surface. Further, the measurement setup comprises a vibration source 14 which is
10 fixed to the testing apparatus 13. According to the embodiment shown in Figure 3, the vibration source 14 is mounted to a bottom surface opposite to the top surface of the testing apparatus 13. Alternatively, the vibration source 14 may also be mounted to the top surface of the testing
15 apparatus 13. The vibration source 14 is configured to apply a vibration to the testing apparatus 13. The vibration source 14 may be an electromechanical exciter or a piezoelectric vibration source.

20 The testing apparatus 13 is configured to be moved according to a predefined movement pattern. In particular, the testing apparatus 13 is configured to be tilted relative to one axis or to be tilted relative to multiple axis. In particular, according to the predefined movement pattern, the testing
25 apparatus 13 is tilted at a defined angular rate in different directions. This predefined movement pattern is well-known with a high precision.

The MEMS device 1 comprises the inertial sensor 2. In
30 particular, the MEMS device 1 may comprise the inertial measurement unit 4 configured to measure inertial movements with respect to six or nine axes. The inertial sensor 2 may comprise one or more gyroscopes. In particular, the MEMS

device 1 may be the device shown in Figure 1 or the device shown in Figure 2.

For measurement of the behaviour of the MEMS device 1, a vibration is applied to the testing apparatus 13 and, thereby, to the MEMS device 1 by the vibration source 14. At the same time, the MEMS device 1 is moved according to the predefined movement pattern.

The output data provided by the inertial sensor 2 are read out and compared to the predefined movement pattern. This allows to determine an error which results from the vibration being applied to the MEMS device 1.

The output data provided by the inertial sensor 2 are analysed and a software algorithm determines whether the deviation of the output data from the predefined movement pattern is within a predefined acceptance limit. This allows to determine whether the MEMS device 1 has an attenuation behaviour that is within given customer specifications.

The output data provided by the inertial sensor 2 may first be evaluated in a sensor fusion algorithm comprising a Kalman filter. The sensor fusion algorithm may be carried out in the ASIC inside the MEMS device 1. Alternatively, raw output data provided by the inertial sensor 2 may be applied to an evaluation unit outside of the MEMS device 1 and the sensor fusion algorithm may be performed in the evaluation unit outside of the MEMS device 1.

30

The testing apparatus 13 further comprises a 3-axis accelerometer 20.

Figure 4 shows an example of the output data provided by the MEMS device 1 in response to a movement of the testing apparatus 13 and a simultaneous vibration being applied by the vibration source 14. The output data shown in Figure 4 are the output data provided by the sensor fusion algorithm wherein the raw data provided by the inertial sensor 2 have been evaluated using a Kalman filter. On the horizontal axis, a time after the start of the measurement in seconds is shown. On the vertical axis, the angle of rotation as calculated from the output data is shown wherein the output data have been evaluated using a sensor fusion algorithm.

It can be seen in Figure 4 that the output data result in a rather smooth curve. Thus, the data show that the inertial sensor 2 was able to perform a reliable measurement even when the MEMS device 1 is vibrated.

Figure 5 shows the result of another measurement. On the horizontal axis, a time after the start of the measurement in seconds is shown. On the vertical axis, the angle of rotation as calculated from the output data is shown wherein the raw output data are shown which have not been evaluated using a sensor fusion algorithm. The inertial sensor 2 is a gyroscope. It is clearly visible in the data shown in Figure 5 that a vibration has been applied with the resonance frequency of the inertial sensor 2 at the time of 0.0 seconds. Due to the resonance behaviour of the gyroscope, the raw data provided by the inertial sensor 2 shown a large error and cannot be considered as being reliable.

Figure 6 shows the result of another measurement wherein a MEMS device 1 has been moved according to a predefined movement pattern and, simultaneously, vibrated. On the

horizontal axis, a time after the start of the measurement in seconds is shown. On the vertical axis, a difference between the roll angle of the testing apparatus 13 which is known in the predefined movement pattern and the roll angle as
5 calculated by a sensor fusion algorithm is shown. It is shown in Figure 6 that the roll angle as calculated by the sensor fusion algorithm deviates from the actual roll angle up to -7° . This deviation is due to resonance effects. Thus, this measurement shows that a damping provided by the damping
10 structure was not strong enough to guarantee reliable data in this case.

Figures 7 and 8 show the result of another measurement of this kind. In Figures 7 and 8, the same measurement is shown,
15 only the scale of the respective vertical axis differs. Again, a time after the start of the measurement in seconds is shown on the respective horizontal axis. On the vertical axis, a difference between the roll angle of the measurement table which is known in the predefined movement pattern and
20 the roll angle as calculated by a sensor fusion algorithm is shown.

A vibration has been applied from the start of the measurement at 0.0 seconds until 8.5 seconds. It can be seen
25 in both figures that, after the vibration stops, the inertial sensor is damped very fast and provides reliable data less than 0.1 seconds after the end of the vibration. Thus, the measurement allows to determine the performance of the damping structure.

30 The above-described measurement can be performed simultaneously for multiple MEMS devices 1. In particular, multiple MEMS devices 1 can be mounted onto the testing

apparatus 13 and evaluated simultaneously. Thus, the measurement is suitable for a mass production of a multitude of MEMS devices 1. The measurement may be performed after a manufacturing process of the multitude of MEMS devices 1 has
5 been completed as part of a performance and reliability test of the MEMS devices 1.

In particular, the measurement can be performed after the MEMS device 1 has been encapsulated with the cap 9.
10 Accordingly, no further production steps have to be performed after the measurement which could, otherwise, influence the damping behaviour.

The measurement can be performed and evaluated very fast.
15 This also helps to enable the measurement for mass production of multiple MEMS devices 1.

Figure 9 shows another method of measuring the behaviour of the MEMS device 1. First, a vibration is applied to the MEMS
20 device 1. Further, a laser beam 15 is applied to the inertial sensor 2. The vibration of the inertial sensor 2 is determined by a laser Doppler vibrometer using the laser beam 15. The cap 9 comprises a hole 16 wherein the laser beam 15 can access the inertial sensor 2 through the hole 16. In an
25 alternative embodiment, the cap 9 is transparent for the laser beam 15.

Reference numbers

	1	MEMS device
	2	inertial sensor
5	3	damping structure
	4	inertial measurement unit
	5	carrier
	6	spring element
	7	stand-off
10	8	bump
	9	cap
	10	bottom surface of the inertial measurement unit
	11	airgap
	12	top surface of the carrier
15	13	testing apparatus
	14	vibration source
	15	laser beam
	16	hole
	20	3-axis accelerometer
20		
	P1	first electrical contact
	P2	second electrical contact
	P3	external contact

25

Claims (We claim)

1. Method for measuring a behaviour of a MEMS device (1) comprising a 6-axis or 9-axis inertial sensor (2),
5 wherein the method comprises the steps of:
A. Mounting the MEMS device (1) to a testing apparatus (13) that comprises a vibration source (14),
B. Applying a vibration to the MEMS device (1) by the vibration source (14) and, simultaneously, moving the
10 testing apparatus (13) according to a predefined movement pattern,
wherein the method further comprises the steps of:
C. Reading output data provided by the inertial sensor (2) and comparing the output data to the predefined
15 movement pattern,
and/or
D. Reading output data provided by the inertial sensor (2) and calculating a frequency response curve of the inertial sensor (2).
20
2. Method according to claim 1,
wherein the testing apparatus (13) comprises a 3-axis accelerometer configured to measure a frequency of a vibration applied to the MEMS device,
25 wherein, in step B, the frequency of the applied vibration is varied, and
wherein, in step D, the frequency response curve is calculated based on the output data by the inertial sensor (2) and the data provided by the 3-axis
30 accelerometer.

3. Method according to claim 1 or 2,
wherein, in step C, a software algorithm determines
whether the difference between the output data provided
by the inertial sensor (2) and the predefined movement
5 pattern is within a predetermined acceptance limit.
4. Method according to one of the preceding claims,
wherein according to the predefined movement pattern,
the testing apparatus (13) is tilted at a defined
10 angular rate in different directions during step B, and
wherein a roll angle and a pitch angle are calculated
based on the output data provided by the inertial sensor
(2) in step C.
- 15 5. Method according to one of the preceding claims,
wherein in step C and/or in step D, the output data
provided by the inertial sensor (2) are evaluated using
a sensor fusion algorithm comprising a Kalman filter
before comparing the output data to the predefined
20 movement pattern.
6. Method according to one of the preceding claims,
wherein the inertial sensor (2) comprises a gyroscope.
- 25 7. Method according to one of the preceding claims,
wherein the inertial sensor (2) is resiliently mounted
on a carrier by means of spring elements,
wherein an air gap is provided between a top surface of
the carrier and a bottom surface of the inertial sensor
30 (2),
wherein a damping structure is applied to at least one
surface chosen from a first surface located on the

carrier and a second surface located on the inertial sensor (2).

8. Method according to the preceding claim,
5 wherein the damping structure is applied as a layer between the inertial sensor (2) and the carrier on one of first and second surface,
wherein the layer comprises recesses, and
wherein the recesses are at least measured to
10 accommodate the spring elements.
9. Method according to one of claims 7 or 8,
wherein the spring elements comprise an elongated structure that is linear, bent or angled,
15 a first end of the extended structure is coupled to a first anchor point on the carrier,
a second end of the extended structure is coupled to a second anchor point on the sensor system,
the height of the air gap normal to the surface is
20 smaller than the distance normal to the surface between first and second anchor point.
10. Method according to one of the preceding claims,
wherein the inertial sensor (2) is encapsulated in a
25 sealed package.
11. Method according to one of the preceding claims,
wherein multiple MEMS devices (1) are mounted to the testing apparatus (13) in step A and wherein the
30 behaviour of multiple MEMS devices (1) is measured simultaneously in steps B and C.

12. Method according to one of the preceding claims,
wherein the vibration is applied continuously or
discontinuously during step B.

5 13. Method according to one of the preceding claims,
wherein the testing apparatus (13) is rotated at an
angular rate in the range of 0.001 deg/s to 1000 deg/s
during step B.

10 14. Method according to one of the preceding claims,
wherein the vibration source (14) vibrates with a
frequency in the range of 0.1 kHz to 1000 kHz during
step B and with an amplitude in the range of 1 nm to 10
µm during step B.

15

15. Method for measuring the behaviour of a MEMS device (1)
comprising an inertial sensor (2),
wherein the method comprises the step of:
applying a vibration to the inertial sensor (2) and
20 measuring the attenuation of the vibration using a laser
Doppler vibrometer.

16. Method according to claim 15,
wherein the MEMS device (1) comprises a cap which seals
25 the inertial sensor (2), wherein the cap is transparent
for a laser beam used in the laser Doppler vibrometer,
or
wherein the MEMS device (1) comprises a cap which covers
the inertial sensor (2), wherein the cap has one or more
30 holes,
wherein a laser beam is applied to the inertial sensor
(2) through one of the holes, wherein the one or more

holes are sealed after measuring the attenuation of the vibration.

Fig. 1

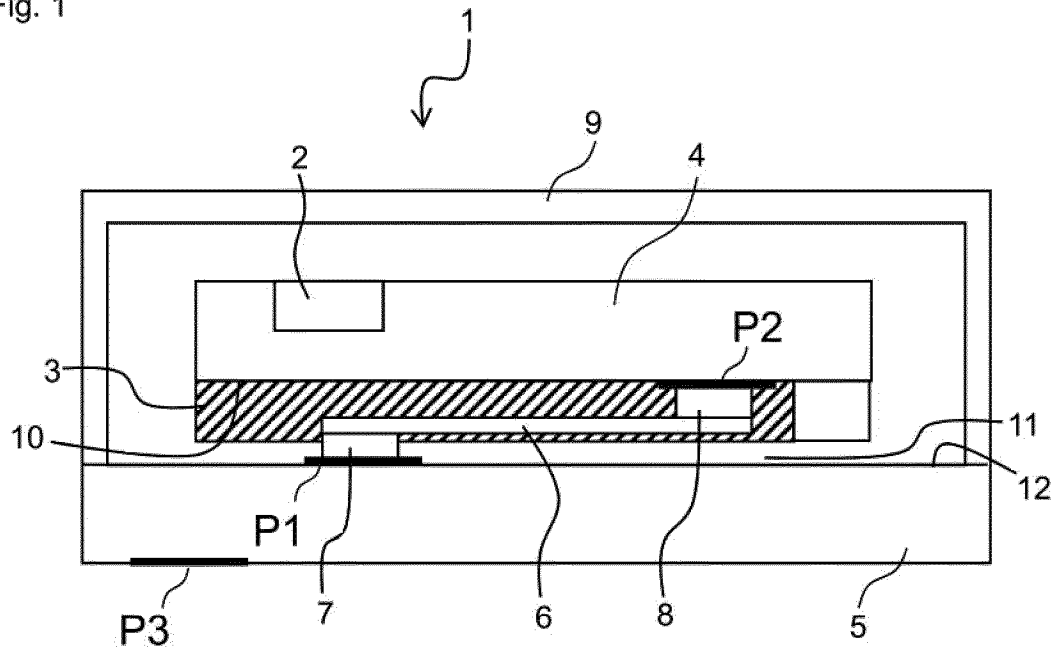


Fig. 2

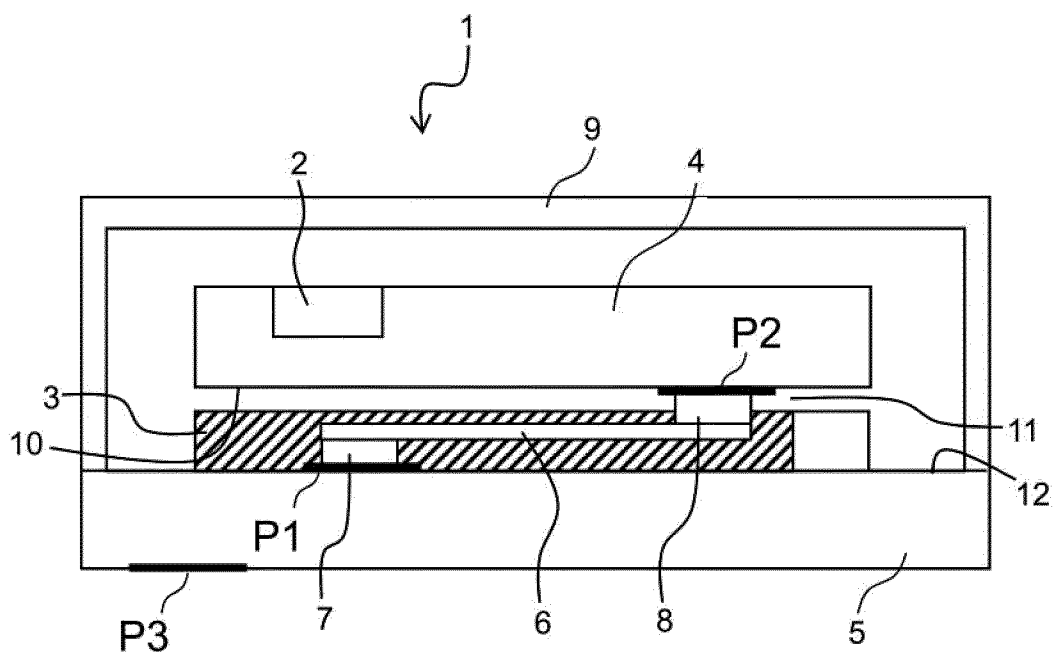


Fig. 3

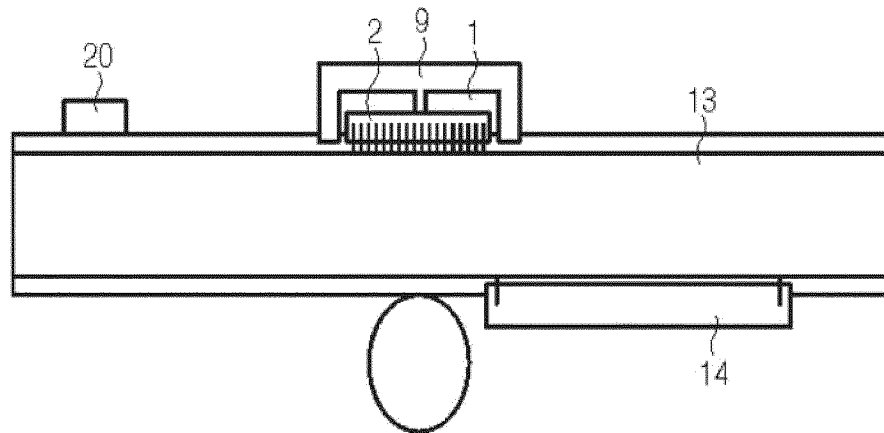


Fig. 4

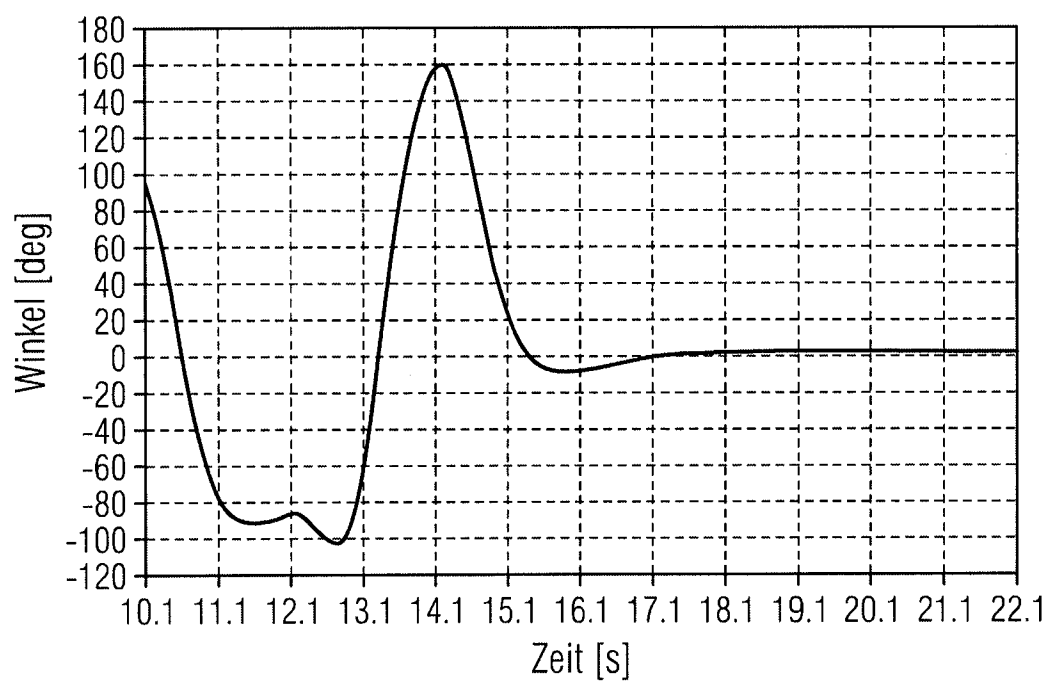


Fig. 5

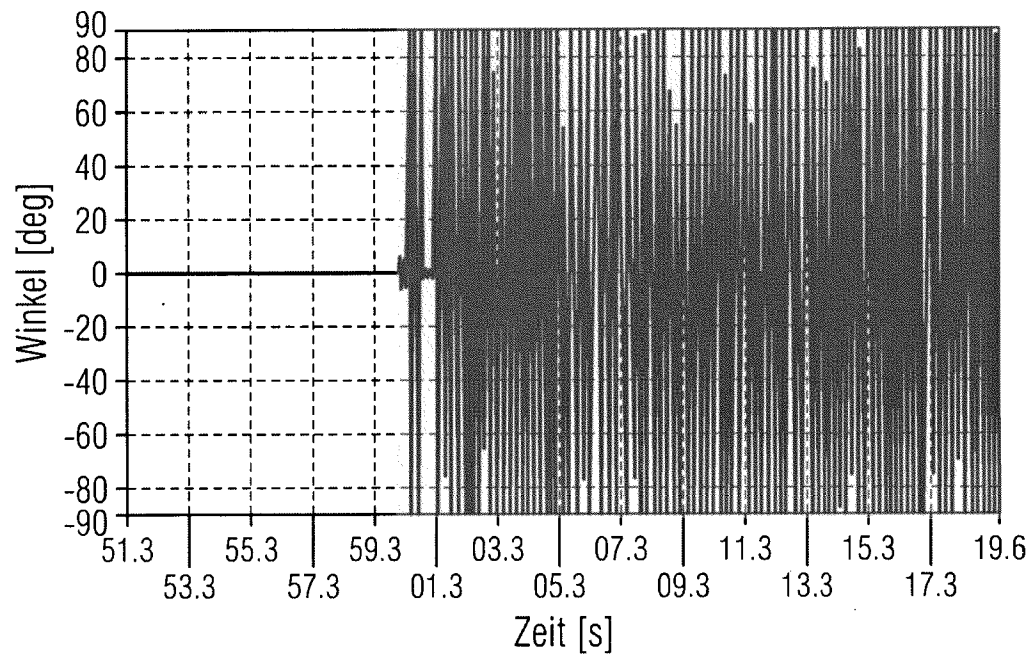


Fig. 6

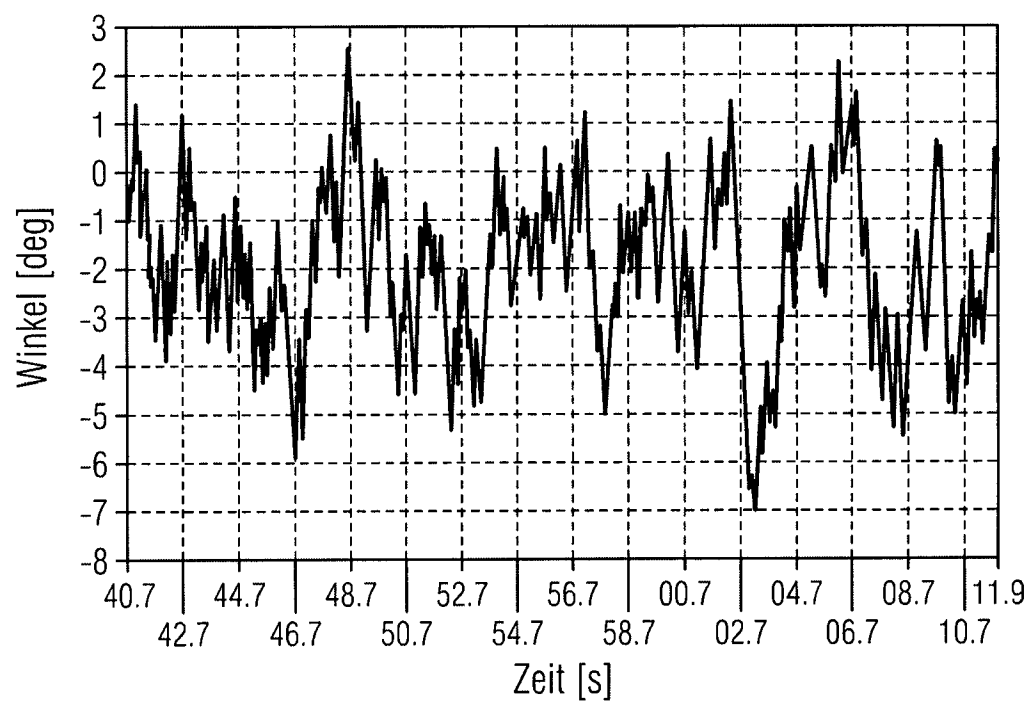


Fig. 7

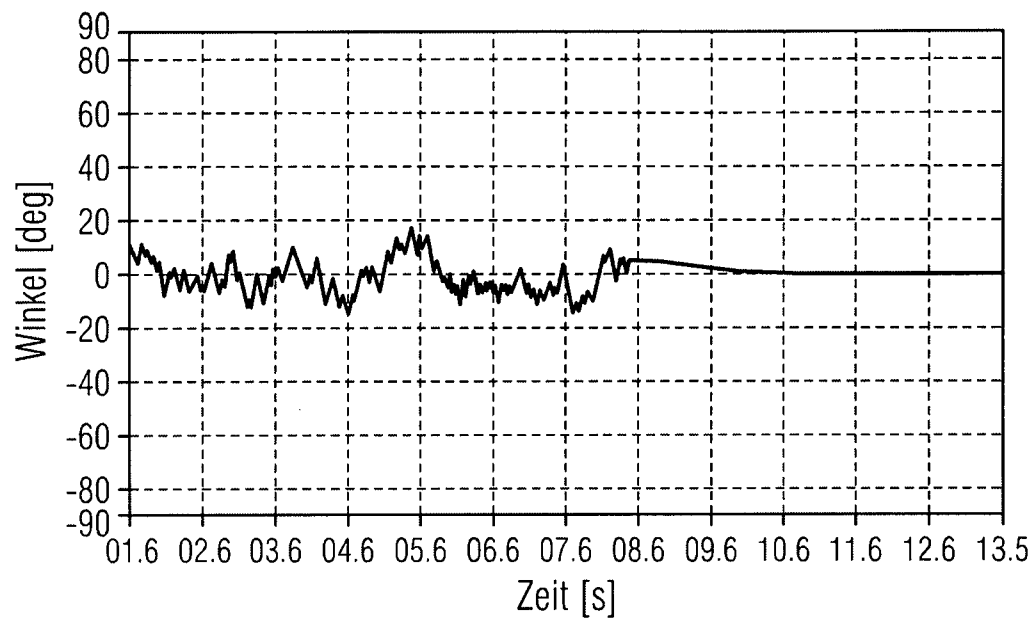


Fig. 8

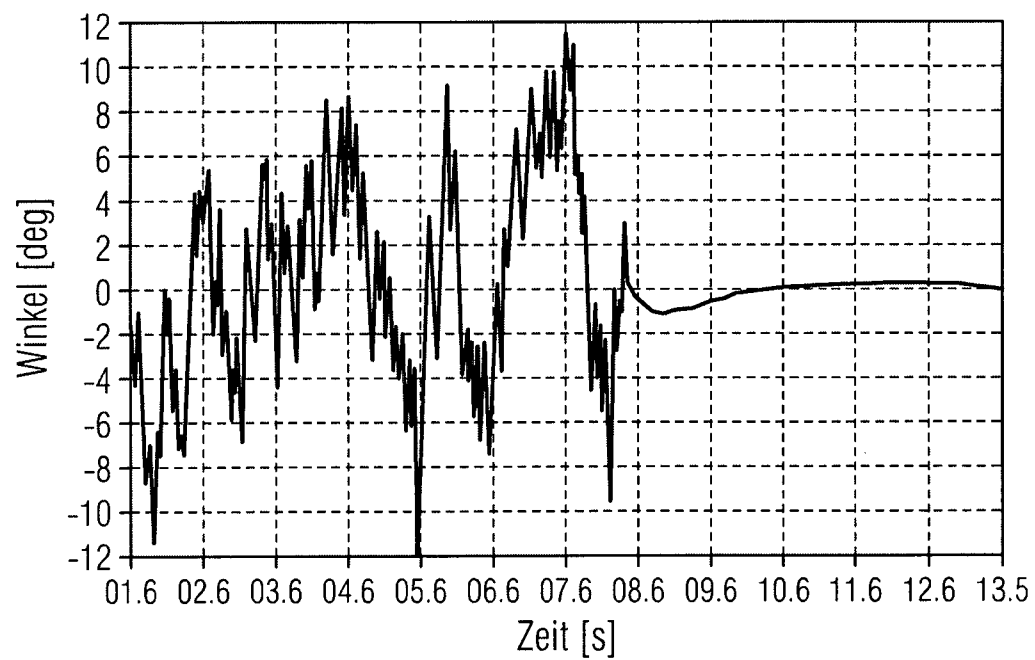
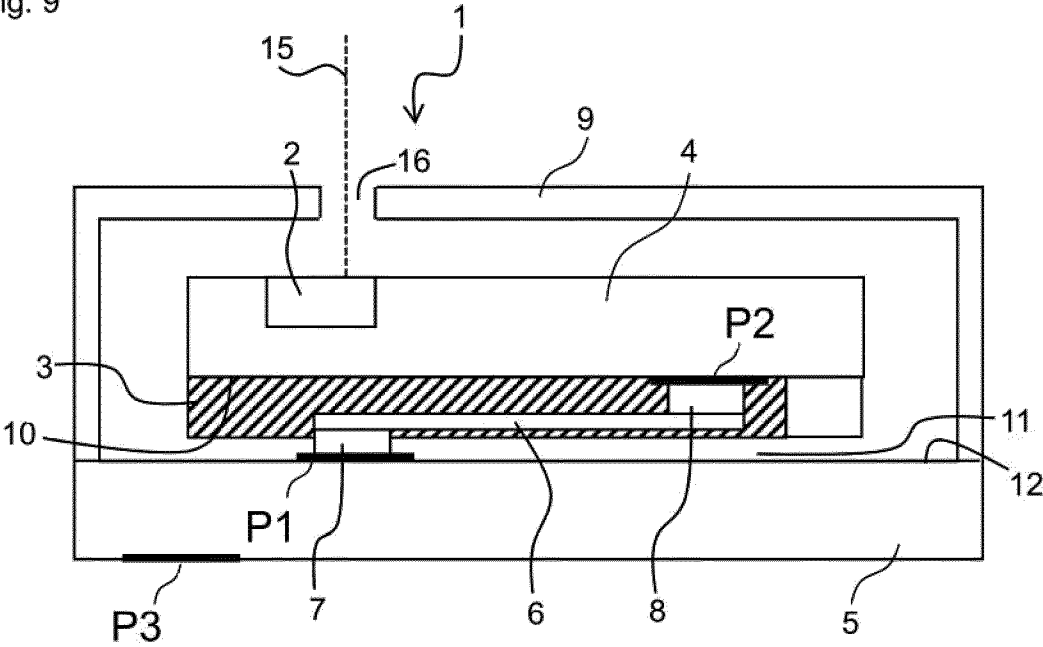


Fig. 9



INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2018/068649

A. CLASSIFICATION OF SUBJECT MATTER

INV. B81C99/00

ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B81C G01M B81B G01C

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	NEKRASOV YAKOV A ET AL: "MEMS gyro vibration immunity and its measurement with TIRA shaker", 2015 IEEE INTERNATIONAL INSTRUMENTATION AND MEASUREMENT TECHNOLOGY CONFERENCE (I2MTC) PROCEEDINGS, IEEE, 11 May 2015 (2015-05-11), pages 1763-1768, XP033171315, DOI: 10.1109/I2MTC.2015.7151547 section "II. MEMS gyro description" section "III. Behaviour of TIRA shaker table with different fixtures" ----- -/-	1-14



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

12 October 2018

Date of mailing of the international search report

03/01/2019

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Meister, Martin

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2018/068649

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GIACCI FEDERICO ET AL: "Signal integrity in capacitive and piezoresistive single- and multi-axis MEMS gyroscopes under vibrations", MICROELECTRONICS AND RELIABILITY, vol. 75, 20 June 2017 (2017-06-20), pages 59-68, XP085154061, ISSN: 0026-2714, DOI: 10.1016/J.MICROREL.2017.06.019	1-6, 11-14
Y	figures 3, 4, 5 section "4. Methodology and results"	7-10
A	US 2011/260734 A1 (LIAO SHYH-SHYAN [TW] ET AL) 27 October 2011 (2011-10-27) paragraphs [0001] - [0003], [0007]	1-14
Y	WO 2017/054868 A1 (TDK CORP [JP]) 6 April 2017 (2017-04-06) figures 2,3 page 13, line 25 - page 15, line 7	7-10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP2018/068649

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-14

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-14

Measuring behaviour of an inertial sensor while vibrating
and moving same

2. claims: 15, 16

Measuring attenuation in an inertial sensor

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2018/068649

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 2011260734	A1	27-10-2011	NONE	

WO 2017054868	A1	06-04-2017	CN 108025906 A	11-05-2018
			EP 3356286 A1	08-08-2018
			JP 2018535101 A	29-11-2018
			US 2018244515 A1	30-08-2018
			WO 2017054868 A1	06-04-2017
