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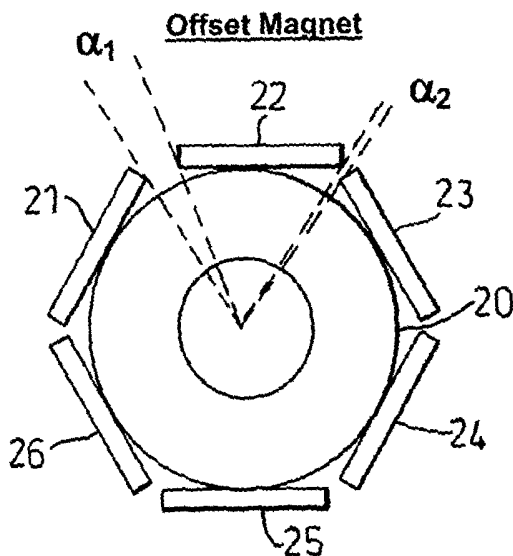
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(54) Title: ANGULAR VELOCITY SENSOR



(57) Abstract: An angular velocity sensor for a rotor (2) and method of determining angular velocity in which the position at which event generation means (4) pass sensing means (5) is determined using information from the times at which the event generation means (4) passed the sensing means (5) during at least one previous complete revolution to of the rotor (2). Especially applicable to use of Hall Effect Sensors to detect commutation points of a brushless permanent magnet rotor in an Electric Power Assisted Steering apparatus.



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ANGULAR VELOCITY SENSOR

This invention relates to improvements in angular velocity sensors, and in particular to an angular velocity sensor suitable for determining the angular position of the rotor in an electrical motor. It also relates to a method of determining the angular velocity of a rotor.

In this description the term "rotor" has been used to describe a device or element which is free to rotate about an axis. It may commonly comprise the rotor of an electric motor and indeed the invention primarily arose from work into monitoring the angular position of rotors in motors for subsequent use in a motor control strategy. However, it is to be understood that the term is not to be construed in the narrow sense and should instead be given a broader interpretation which includes - amongst other things - steering shafts for vehicle steering systems.

To measure the angular position of a rotor a wide variety of angular position sensors have been developed. The most common way of determining the angular velocity of a rotor is to provide a sensor, which determines the elapsed time taken for a fixed position on the rotor to make a complete revolution. The faster the rotor is spinning the shorter the elapsed time taken for the fixed point to pass the sensor and complete a revolution before passing the sensor again.

A problem with sensing the passing of a fixed point on a rotor is that a velocity value is only produced once for each complete revolution. If the rotor is turning relatively slowly the update time for the velocity value may be too long for accurate measurements to be obtained. To improve on the response time of the sensor it is therefore common to provide a number of different fixed points equally spaced around the rotor. For example, four points at 90 degrees spacing may be provided. In this case

a velocity signal can be generated when the rotor has passed through a quarter of a revolution.

5 An example of a widely used angular velocity sensor which produces more than one output for each revolution of the rotor is the use of a Hall effect sensing device to detect the passing of the poles of the magnets of an electric motor.

10 The state of the Hall effect sensors changes whenever a magnet edge passes the sensing region of the elements. Thus, the passing of the rotor magnets defines the fixed measurement points used by the sensor. As more than one magnet is used then more than one fixed point is provided within each revolution.

15 A problem common to any system in which a number of fixed points are detected as a rotor rotates arises due to inaccuracies in the positioning of the fixed points. In a simple system the fixed points are arranged at equal angular spaced positions as illustrated in Figure 2(a) of the accompanying drawings. Six magnets 21,22,23,24,25,26 are spaced at equal angles α around a rotor 20.

25 If the angular spacing is known then the velocity is readily determined by measuring the elapsed time between adjacent fixed points passing the sensor. However, if the fixed points are not accurately positioned the spacing between adjacent points will vary and so the velocity determined simply from the elapsed time will also seem to vary even if the rotor is rotating at a constant speed. This is illustrated in Figure 2(b) of the accompanying drawings. The spacing α_1 and α_2 between two pairs of the magnets 21,22 and 22,23 is clearly unequal.

30

We have found that the exact angular position of the magnets of a practical rotor will be uncertain due to manufacturing tolerances and constraints associated with the attachment of the magnets to the rotor. This will cause the transitions between magnets to occur slightly before or
5 after the expected angular transition point as the rotor is rotated. This misalignment is often random and cannot be predicted.

The problem of misalignment does not occur when only one fixed point is provided, as there will always be a complete revolution occurring
10 between each sensing of the fixed point. For this reason, prior art velocity techniques have relied upon measurement over a complete revolution where high accuracy is needed or have simply tolerated the errors that occur due to misalignment.

15 It is an object of the present invention to provide an angular position sensor, which overcomes the problems associated with misalignment of the fixed points on a rotor. It is a further object of the present invention to provide a method of monitoring the angular position of rotor which is at least partially free from the problems associated with incorrect
20 alignment of fixed sensing points such as rotor magnets described hereinbefore.

In accordance with a first aspect the invention provides an angular velocity sensor for detecting the angular velocity of a rotor, the sensor
25 comprising:

at least two event generating means located at angularly spaced positions around the rotor;

angular position sensing means which is adapted to produce a plurality of temporally spaced events as the rotor is rotated about its axis relative to
30 the sensing means, each event occurring as a respective event generating means passes the sensing means,

event time measurement means adapted to record the time at which the respective sensed events occur;

event position determining means adapted to determine the angular position of the rotor at the time the events occur;

5 and velocity determining means adapted to determine the average velocity of the rotor between two temporally spaced events based upon the measured times at which the events occur and the determined angular position of the rotor when the events occur,

characterised in that the event position determining means
10 determines the relative angular position of the two event generating means from information previously obtained from the event time measurement means during at least one previous complete revolution of the rotor.

The invention thus provides apparatus in which information obtained from
15 measurements of the times at which events occurred during a previous revolution of the rotor is used to determine the relative angular positions of the event generating means. This allows the apparatus automatically to be insensitive to the misalignment errors that can occur where two or more event generating means are spaced around a rotor. Instead of
20 assuming that the events occur at "ideal" fixed locations, the apparatus actually determines where the event generating means are located to allow an accurate velocity value to be determined.

The event position determining means may be adapted to determine the
25 relative angular positions of the event generation means from measurements obtained during an initial testing operation of the apparatus.

The determined position values may be stored in a memory for subsequent
30 use by the apparatus. Alternatively, the event position determining means may update the values at regular intervals during operation of the rotor or

perhaps even continuously. They may be updated whenever the sensor is started up after each period in which it has been laid dormant.

The event position determining means may comprise:

- 5 first means for determining the elapsed time taken for the rotor to complete a full revolution,
- second means for determining the average velocity over the complete revolution from the elapsed time,
- third means for determining the elapsed time between two events that
- 10 occurred during the complete revolution, and
- fourth means for determining the displacement of the rotor between the two events based upon the average velocity from the second means and the elapsed time from the third means.

- 15 Because the average velocity is taken for a full revolution it can be calculated with high accuracy since it is free from any misalignment errors of the event generating means. This is then used with the time measurements for the two events within the revolution to determine their relative positions.

20

It is possible to use the average velocity obtained over a complete revolution to determine the angular displacement between every pair of temporally adjacent events that occurred in that revolution. However, such an approach is not preferred.

25

- Consider that the rotor is in a steady state of constant velocity, steady deceleration or steady acceleration over the measured complete revolution. In all three cases the average velocity over the complete revolution will provide an accurate measurement of the average velocity
- 30 of the rotor at the instant at which the rotor is halfway through the

revolution. At other points within the revolution it will be inaccurate unless the rotor is operating at a constant velocity.

In view of this we have appreciated that the average velocity should only
5 be used when determining the relative angular positions of events that occur at or around the half way point through the revolution.

The apparatus may therefore determine a set of average velocity values, each one corresponding to a full revolution that starts at the time of a
10 different event, and employ this average to determine the relative position of those events at or around half a revolution earlier in the complete revolution.

It will therefore be appreciated that it is not essential that the angular
15 position of every pair of events is determined from information obtained during a single revolution of the rotor. Timings may be taken for a first pair of events during one revolution to determine the relative angular positions. Timings may also be taken some time later from a different revolution to determine the relative angular position of a different pair of
20 events.

In many cases, the ideal position of each of the event generating means will be known. They will typically be uniformly spaced around the rotor. In this case, instead of storing values indicative of the actual relative
25 positions of the event generating means a set of error correction values may be stored representing the amount that each event generating means deviates from its ideal position.

The error correction value may be stored in the memory as well as or
30 instead of the determined angular position values. An error correction

value may be determined for, and stored for, each event over a complete revolution of the rotor.

To determine the error correction values it is essential for the apparatus
5 to store in the memory a set of ideal angular position values for each
event that occurs over a revolution. This may comprise a set of data
values, or a stored function from which the ideal position can be
determined. For example, the number of events per revolution and their
ideal angular spacing may be stored in the memory.

10

In effect, the storage means will contain a set of error values, or actual
angular position values, for each event that occurs as the rotor rotates.
Thus, whenever an event occurs the error can be taken into account to
indicate the correct angular position of the rotor at the time the event
15 occurred.

The event generating means may comprise magnets spaced around the
rotor and the sensing means may comprise one or more, and preferably
three, electromagnetic sensors. Suitable sensors are those which use the
20 Hall effect to detect the passing of the poles of a magnet.

The time measurement means may comprise a counter. The counter may
be triggered whenever an event occurs and be stopped whenever a
subsequent event occurs. The total count between events will provide an
25 indication of the time between events. Of course, many other devices for
measuring the elapsed time between temporally spaced events are
possible.

In accordance with a second aspect the invention provides a method of
30 determining the angular positions of at least two event generating means

located at angularly spaced positions around a rotor, the method comprising the steps of:

producing a plurality of temporally spaced events as the rotor is rotated about its axis relative to a sensing means, each event occurring as a
5 respective event generating means passes the sensing means over a complete revolution,

recording the time at which the respective sensed events occur;

determining the time taken for the rotor to rotate through the complete revolution,

10 determining the average velocity of the rotor across the complete revolution from the elapsed time for the complete revolution; and

determining the relative angular position of the two event generating means from the determined average velocity for the complete revolution and the elapsed time between the measurements of the two events within

15 that complete revolution.

The method therefore combines elapsed time measurements for two events within a revolution with an average determined across a complete revolution to determine the actual positions at which the events occurred.

20

The time taken to complete a revolution may be determined by measuring the elapsed time taken for one of the event generating means to generate two temporally spaced events.

25 Each event generating means may produce a unique identifiable event allowing it to be uniquely identified to do this. Alternatively, if the total number of event generating means is known the passing of a complete revolution may be determined by counting the number of events that have occurred.

30

The method may comprise determining a set of average velocity values, each one corresponding to a full revolution of the rotor that starts at the time of a respective event, with each average being used to determine the relative displacement between events that occur at or around half a revolution earlier in the respective complete revolution from which the average velocity was obtained.

Whilst the method can be used with only two event generating means it is suitable for use with many more than two. In practice, for n event generating means there will be n relative angular positions to determine. This can be achieved using the method of the present invention by measuring the time for a complete revolution starting with event $n = m$ (for $m = 1$ to n), determining the average velocity of the rotor over that complete revolution, and combining this average velocity with the elapsed time between events occurring approximately halfway through that revolution (i.e. $n = m/2$). This provides the greatest accuracy. However, if it can be determined that the rotor rotated at a steady constant velocity throughout its revolution then a single average value can be reliably used to determine the relative position of every event in that revolution.

The method may comprise storing a rolling set of n timing values from the n event generating means. Thus, at the instant of any event occurring the times of the n previous events will be stored in the buffer.

The method may then comprise determining the total elapsed time taken for a complete revolution up to the instant of the current event by adding together the total times held in the buffer for the n previous events. The average velocity for a revolution may be determined from this elapsed time.

30

Finally, the method may comprise determining the elapsed time between two events at or around the centre of rolling set of values and combining this elapsed time with the average velocity to determine the angular displacement of the rotor between the two events and hence their relative
5 angular positions. This may be stored in a memory.

The method may be repeated for each event time an event occurs over a full revolution until a full set of n relative position values are stored.

10 Once the full set of position values is stored the method may be stopped or may be continuously updated as the rotor turns.

Having stored the full set of position values they may be used to determine the velocity of the rotor by monitoring the time at which events
15 occur, identifying which events have occurred, determining the displacement of the rotor between the events from the stored values, and dividing the displacement by the elapsed time to determine the velocity.

In accordance with a third aspect the invention provides a method of
20 determining the angular velocity of a rotor comprising the initial steps of determining the position of a plurality event generating means spaced around the rotor using the method of the second aspect of the invention, and subsequently measuring the elapsed time between events together with the angular position at which the event occurred to determine the velocity
25 of the rotor.

There will now be described by way of example only one embodiment of the present invention with reference to the accompanying drawings of which:

Figure 1 is cross sectional view of a motor which is monitored by a velocity sensor in accordance with a first aspect of the invention;

Figure 2(a) is a cross-sectional view of a rotor having perfectly spaced rotor magnets and **2(b)** illustrates the same rotor having imperfectly aligned rotor magnets;

Figure 3 is a schematic of the sensor of the present invention;

Figure 4 illustrates the contents of the rolling buffer in the memory of the sensor after a complete revolution; and

Figure 5 shows how the contents of the buffer shown in **Figure 4** changes as the next event occurs.

The angular velocity sensor illustrated by way of example in the accompanying drawings is especially suited to the monitoring of the angular position of an electric motor illustrated in **Figure 1**. The motor 1 comprises a 3-phase star-connected brushless permanent magnet (PM) configuration. Its electromagnetic design includes a 6-pole permanent magnet rotor 2 and 9-slot copper-wound stator 3. The six magnets 4 are generally evenly spaced around the rotor. As the rotor 1 rotates through one complete mechanical revolution there are six PM north-south pole transitions seen at any point on the stator.

A Hall Effect Array 5 is secured to the stator which comprises three electromagnetic sensors (not shown) spaced around the rotor at 40 degree mechanical spacing. Each sensor can adopt one of two polarisation states as the north and south poles of magnets on the rotor pass by. Each of the Hall effect sensors changes from one state to another as the motor rotates. The pattern of the sensor output can adopt six different states to indicate

the electrical position of the motor as illustrated in Figure 2 of the accompanying drawings. It is notable that the pattern repeats three times within each complete mechanical revolution of the rotor for the type of motor illustrated in Figure 1 of the accompanying drawings, giving a total
5 of 18 transitions of "events" per revolution.

The output of the sensing means 5 is passed to a processor 6 as shown in Figure 3 of the accompanying drawings. The processor 6 also receives a count signal from a timer 7. Each time an event occurs in the output of
10 the Hall effect sensors 5 it is passed to the processor. The processor records the number of the event (from $n=1$ to 18) which is stored in an area of electronic memory 8 associated with the processor 6. The time at which the event occurred (from t_1 to t_{18}) is also stored in the memory in a rolling buffer.

15

After a complete revolution a total of an array of 18 events and their associated time values are stored in a buffer held in the memory. This is illustrated in Figure 4 of the accompanying drawings.

20 Once the buffer is full, as the last event is entered in the buffer, the processor determines the total time for a complete revolution by summing all the times held in the rolling buffer.

From the average time for a revolution the average velocity (degrees per
25 second) of the rotor during the revolution is determined by dividing the time (in seconds) by the angle (360 degrees).

At a constant velocity the average velocity could be used to determine the angular displacement between each adjacent event in the buffer by
30 multiplying the elapsed time between events by the average velocity.

However, if the motor is accelerating or decelerating the average velocity not be correct for all the transition points.

To improve the accuracy of the offset values it is presumed that the motor
5 is constantly decelerating or accelerating or rotating at a steady velocity. If this assumption is made then the average velocity value will be correct for use in determining the offset values for a transition half a revolution earlier. It is therefore at this point that we calculate the offset error.

10 For example, when the full set of 18 times has been calculated the average velocity over the whole set is calculated. This is then used to determine the angular displacement between the 9th and 10th events. This displacement is stored in the memory as illustrated in Figure 4.

15 As the next event is received (event $n=2$ for the second revolution) the time of the first event is pushed out of the rolling buffer and the new event entered as shown in Figure 5. The average velocity of the revolution indicated by the new buffer contents is again calculated. This time the average is used to determine the displacement between the 10th
20 and 11th events. This is also stored in the memory. This is shown in Figure 5.

The process of measurement is continued 18 times until the angular
25 displacements between all adjacent pairs of events are stored in the memory. This provides a measure of the relative angular position of each event.

Once the complete set of offset error values is determined they are used
during subsequent operation of the sensor to determine the exact angular
30 velocity of the rotor. The time between two events is determined and the angular position at which the events actually occurred is found by

identifying the events. The velocity can then be directly found by combining the displacement between events with the elapsed time between events.

CLAIMS

1. An angular velocity sensor for detecting the angular velocity of a rotor, the sensor comprising:
at least two event generating means located at angularly spaced positions
5 around the rotor;
angular position sensing means adapted to produce a plurality of temporally spaced events as the rotor is rotated about its axis relative to sensing means, each event occurring as a respective event generating means passes the sensing means,
10 event time measurement means adapted to record the time at which the respective sensed events occur;
event position determining means adapted to determine the angular position of the rotor at the time the events occur;
and velocity determining means adapted to determine the average velocity
15 of the rotor between two temporally spaced events based upon the measured times at which the events occur and the determined angular position of the rotor when the events occur,
characterised in that the event position determining means determines the relative angular position of the at least two event
20 generating means from information previously obtained from the event time measurement means during at least one previous complete revolution of the rotor.
2. The angular velocity sensor of claim 1 in which the event position
25 determining means is adapted to determine the relative angular positions of the event generation means from measurements obtained during an initial testing operation of the apparatus.
3. The angular velocity sensor of claim 1 or claims 2 in which the
30 event position determining means updates the relative angular positions of

the event generation means at regular intervals during operation of the rotor.

4. The angular velocity sensor of any preceding claim in which the event position determining means comprises:

5 first means for determining the elapsed time taken for the rotor to complete a full revolution,

second means for determining the average velocity over the complete revolution from the elapsed time,

10 third means for determining the elapsed time between two events that occurred during the complete revolution, and

fourth means for determining the displacement of the rotor between the two events based upon the average velocity from the second means and the elapsed time from the third means.

15

5. The angular velocity sensor of claim 4 in which the average velocity obtained over a complete revolution is used to determine the angular displacement between every pair of temporally adjacent events that occurred in that revolution.

20

6. The angular velocity sensor of claim 4 in which the apparatus determines a set of average velocity values, each one corresponding to a full revolution that starts at the time of a different event, and employs these averages to determine the relative position of those events at or around half a revolution earlier in the complete revolution.

25

7. The angular velocity sensor of any one of claims 4 to 6 in which timings are taken for a first pair of events during one revolution to determine the relative angular positions of the first pair of events and some time later from a different revolution to determine the relative angular position of a second pair of events.

30

8. The angular velocity sensor of any preceding claim in which a set of error correction values are stored in a memory, representing the amount that each event generating means deviates from its ideal position.
- 5
9. The angular velocity sensor of claim 8 in which the error correction values are stored in the memory as well as or instead of the determined angular position values.
- 10 10. The angular velocity sensor of claim 8 or claim 9 in which the apparatus stores in the memory a set of ideal angular position values for each event that occurs over a revolution.
11. The angular velocity sensor of any preceding claim in which the event generating means comprises magnets spaced around the rotor and the sensing means comprises at least one electromagnetic sensor.
- 15
12. A method of determining the angular positions of at least two event generating means located at angularly spaced positions around a rotor, the method comprising the steps of:
- 20 producing a plurality of temporally spaced events as the rotor is rotated about its axis relative to a sensing means, each event occurring as a respective event generating means passes the sensing means over a complete revolution,
- 25 recording the time at which the respective sensed events occur;
- determining the time taken for the rotor to rotate through the complete revolution,
- determining the average velocity of the rotor across the complete revolution from the elapsed time for the complete revolution; and
- 30 determining the relative angular position of the two event generating means from the determined average velocity for the complete revolution

and the elapsed time between the measurements of the two events within that complete revolution.

13. The method of claim 12 in which the time taken to complete a
5 revolution is determined by measuring the elapsed time taken for one of the event generating means to generate two temporally spaced events.

14. The method of claim 12 or claim 13 in which each event generating
10 means produces a uniquely identifiable event allowing it to be uniquely identified.

15. The method of claim 12 or claim 13 in which the passing of a
complete revolution is determined by counting the number of events that
15 have occurred, the total number of event generating means being known.

16. The method of any one of claims 12 to 15, in which the method
comprises determining a set of average velocity values each one
corresponding to a full revolution of the rotor that starts at the time of a
20 respective event, with each average being used to determine the relative displacement between events that occur at or around half a revolution earlier in the respective complete revolution from which the average velocity was obtained.

17. The method of any one of claims 12 to 16 in which, if it is
25 determined that the rotor is rotating at a steady constant velocity throughout a revolution, a single average value is used to determine the relative position of every event in that revolution.

18. The method of any one of claims 12 to 17, in which the method
30 comprises storing a rolling set of n timing values from n event generating means.

19. The method of claim 18 in which the method further comprises determining the total elapsed time taken for a complete revolution up to the instant of the current event, and hence the average velocity, by adding
5 together the times for the n previous events.

20. The method of claim 19 in which the method further comprises determining the elapsed time between two events at or around the centre of rolling set of values and combining this elapsed time with the average
10 velocity to determine the angular displacement of the rotor between the two events and hence their relative angular positions.

21. The method of any one of claims 18 to 20 in which the method is repeated for each time an event occurs over a full revolution until a full
15 set of n relative position values are stored.

22. The method of claim 21 in which the full set of position values are used to determine the velocity of the rotor by monitoring the time at which events occur, identifying which events have occurred, determining
20 the displacement of the rotor between the events from the stored values, and dividing the displacement by the elapsed time to determine the velocity.

23. A method of determining the angular velocity of a rotor comprising
25 the initial steps of determining the position of a plurality event generating means spaced around the rotor using the method of any one of claims 12 to 22, and subsequently measuring the elapsed time between events together with the angular position at which the event occurred to determine the velocity of the rotor.

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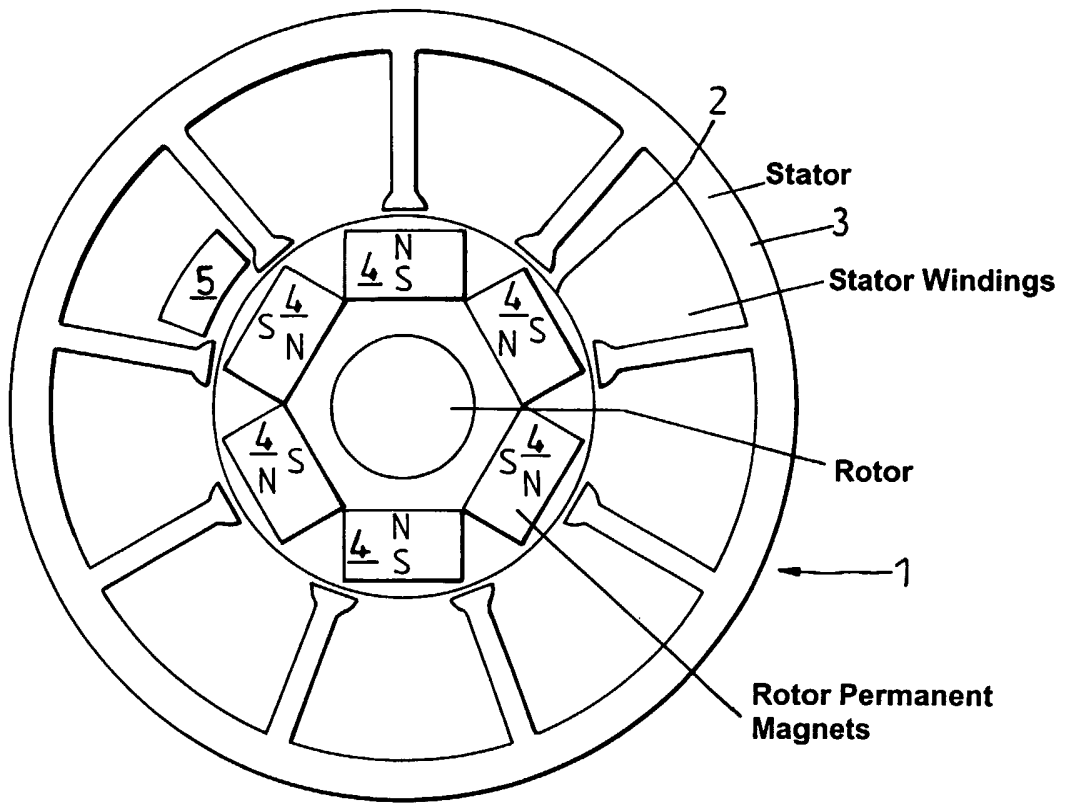


Fig. 1

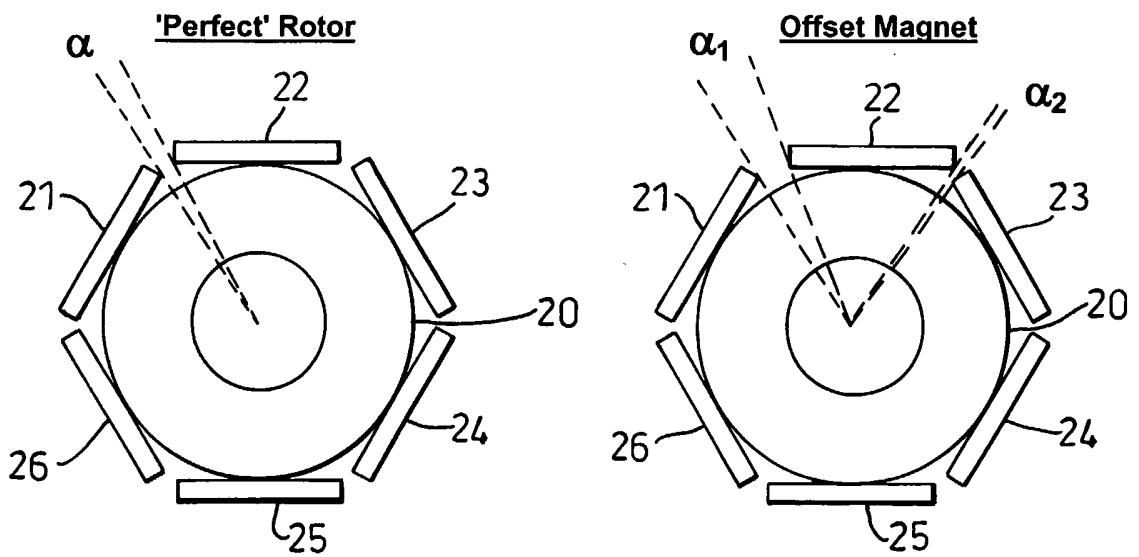


Fig. 2(a)

Fig. 2(b)

2/2

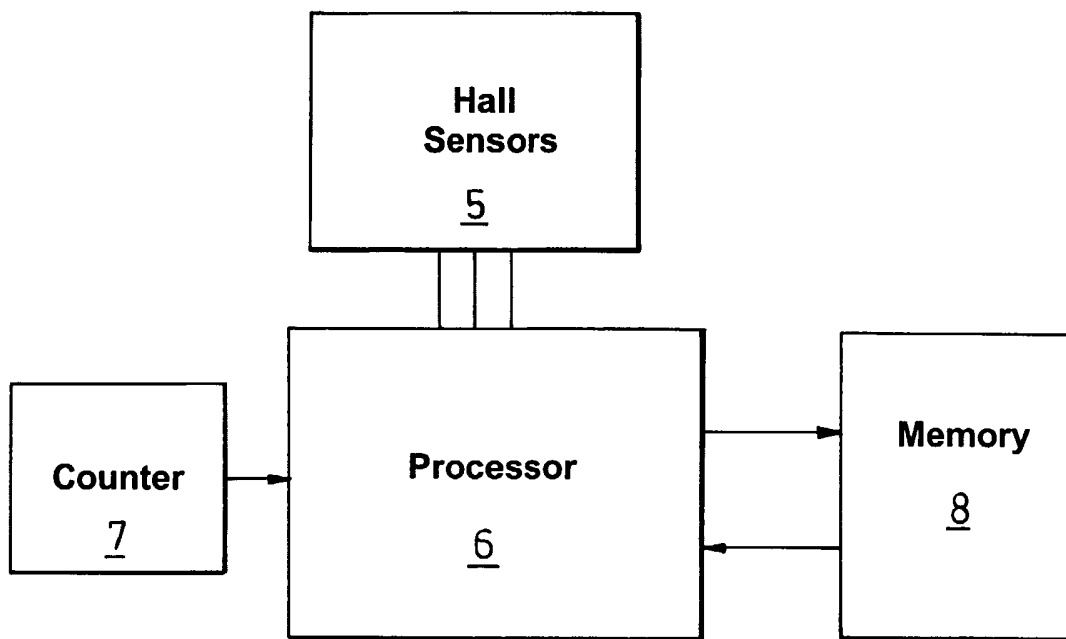


Fig. 3

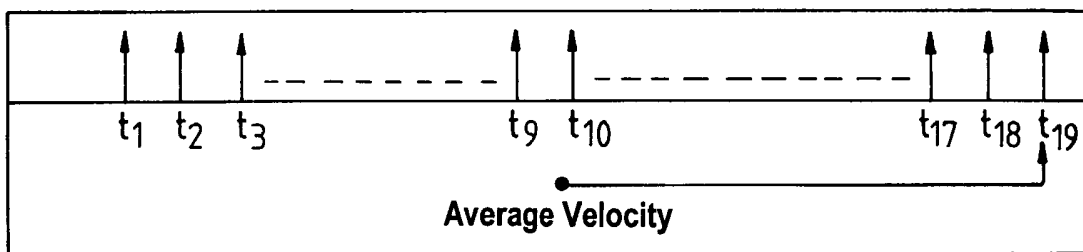


Fig. 4

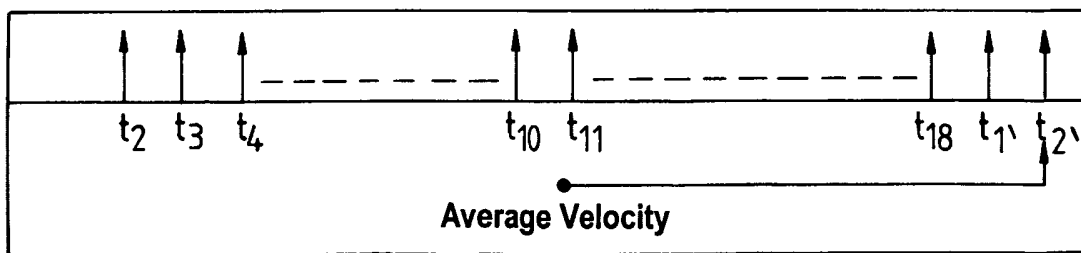


Fig. 5

INTERNATIONAL SEARCH REPORT

Application No
rui/GB 02/05587

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01P3/489 G01P3/487 G01P21/02 G01D5/244 G01D18/00

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)
IPC 7 G01P G01D

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 practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 00 08475 A (BOCK STEFAN ;KOESTLER WERNER (AT); SIEMENS AG (DE); REDELBERGER HA) 17 February 2000 (2000-02-17) page 7, line 9 -page 9, line 2; figures 1-3 ---	1-5, 8-15, 17-19
X	DE 197 47 918 A (MANNESMANN VDO AG) 11 March 1999 (1999-03-11) column 5, line 9 -column 6, line 29; figure 4 ---	1-5, 8-15, 17-19
A	EP 0 902 292 A (BAYERISCHE MOTOREN WERKE AG) 17 March 1999 (1999-03-17) paragraphs '0016!-'0024!; figures 3-5 --- -/--	6,7,16, 20

Further documents are listed in the continuation of box C. Patent family members are listed in annex.

° Special categories of cited documents :

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

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Date of the actual completion of the international search 10 April 2003	Date of mailing of the international search report 23/04/2003
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INTERNATIONAL SEARCH REPORT

Application No
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