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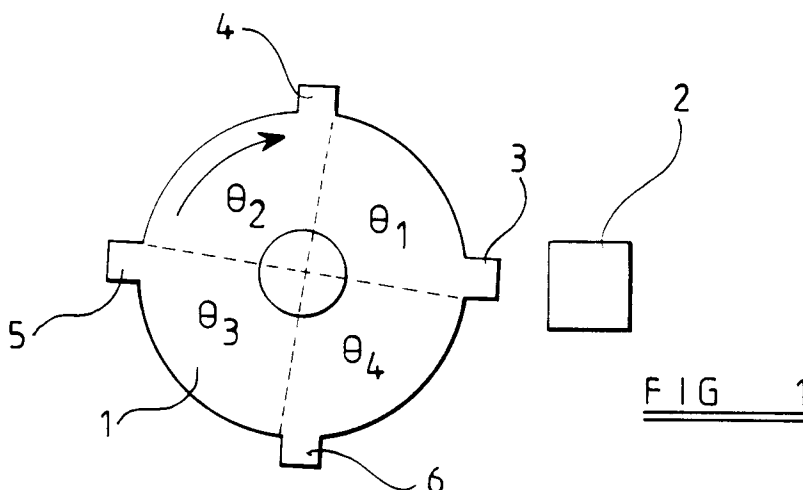
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(54) A method of and an apparatus for calibrating a rotary position transducer

(57) A rotary position transducer comprises a rotary element such as a wheel (1) having a plurality of markers such as teeth (3, 4, 5, 6). A sensor (2), for instance of the variable reluctance type, produces a position signal when each marker (3, 4, 5, 6) passes. In order to calibrate the transducer, the rotary element (1) is rotated

with substantially constant deceleration. First time periods between consecutive position signals are measured for a first revolution of the rotary element (1). Second time periods between consecutive position signals are measured for a second revolution subsequent to the first. Corrected angular spacings are then determined from the first and second time periods.



EP 0 750 105 A1

Description

The present invention relates to a method of and an apparatus for calibrating a rotary position transducer.

Modern internal combustion engines of both spark-ignition and compression-ignition types are controlled by engine management systems based on programmed data processors, for instance microcomputers. Such engine management systems control the amount of air/fuel mixture supplied to the cylinders of the engine and the timing of ignition in each cylinder. In order to perform such control, the engine management system requires signals which indicate the position of the engine output shaft.

A known type of rotary position transducer comprises a toothed wheel, for instance mounted on an engine crankshaft. A variable reluctance transducer cooperates with the toothed wheel to supply a signal, for instance corresponding to the leading edge of each tooth as it passes the sensor. The toothed wheel is machined so that the teeth are nominally equi-angularly spaced. However, because of tolerances in manufacture and in mounting the wheel on the crankshaft, the angular spacing of the teeth is subject to unpredictable errors. In the absence of calibration to assess and compensate for such errors, the sensor output signals supply position information to the engine management system which is affected by these tolerances and this results in reduced accuracy of control of the engine.

DE 4 221 891 discloses a calibration technique in which the time for a complete revolution of a toothed wheel is compared with the time period between consecutive passages of the teeth past the sensor. Differences between the times for each such "sector" and the expected average time for each sector calculated from the time for one complete revolution of the wheel are attributed to tooth errors. To eliminate errors which occur when the engine speed is increasing or decreasing during the calibration, it is possible to perform three successive 360° measurements spaced 120° apart for a six cylinder engine. The error calculations are performed and then averaged.

This technique is performed while an air/fuel mixture is supplied to the engine. Thus, small differences in cylinder-specific combustion effects alter the actual values of calculated sector angles between teeth.

GB 2 134 265 discloses an arrangement for generating rotational speed data for an internal combustion engine.

This technique attempts to compensate for cyclic speed variations but does not perform a calibration of position sensing.

GB 2 198 241 discloses an arrangement for calculating correction coefficients for tooth spacing which assumes uniform crankshaft speed throughout a full revolution of the crankshaft. However, errors arise because of the cyclic nature of the actual crankshaft speed.

SAE Technical Paper No. 930399 "Misfire Detection by Evaluating Crankshaft Speed - A Means to Comply with OBDII", Klenk, Moser, Mueller, and Wimmer suggests that angular deviations between sectors can be calculated on the basis of time period measurements during fuel cut-off conditions. However, no details of a suitable technique are disclosed in this paper.

US 5 117 681 discloses a technique which performs calibration during engine rotation without combustion processes. Performing such calibration with a closed throttle and with fuelling cut off is said to minimise the effects of compression ratio differences among the cylinders of the engine. Calibration is performed by comparing the time period for individual sectors between consecutive teeth with a time period which is unaffected by tooth errors, such as that corresponding to a whole number of engine revolutions. The latter measurement is then compared with an individual sector measurement which is, as far as possible, centred within the measurement without tooth errors. Differences in average speed are assumed to be caused by tooth errors. This technique assumes linear decrease in velocity i.e. constant deceleration, but requires that the individual sector measurement be centralised within, for instance, a 360° measurement. In general, the teeth correspond to top dead centre positions of various engine cylinders. For a six cylinder engine, three teeth and hence three sectors are provided on the toothed wheel so that this requirement can be achieved. However, for an eight cylinder engine requiring four sectors, this requirement cannot be met.

According to a first aspect of the invention, there is provided a method of calibrating a rotary position transducer comprising a rotary element having a plurality of markers and a sensor cooperating with the rotary element to produce a position signal when each marker passes the sensor, comprising the steps of:

rotating the rotary element with substantially constant deceleration;

measuring first time periods between consecutive position signals for a first revolution of the rotary element;

measuring second time periods between consecutive position signals for a second revolution of the rotary element subsequent to the first revolution; and

determining corrected angular spacings between the markers from the first and second time periods.

The rotary element may be driven by an internal combustion engine under closed throttle fuel cut-off conditions. Such conditions provide substantially constant deceleration with respect to revolutions of the crankshaft.

The rotary element may comprise a toothed wheel and the sensor may comprise a variable reluctance sensor.

The markers may be nominally equi-angularly spaced. The number of markers may be equal to the number of firing events per revolution of an engine crankshaft.

The first and second revolutions of the engine may be consecutive revolutions.

The determining step may be based on calculating average speeds during the first and second time periods, subtracting the average speed for each of the second time periods from the average speed during the corresponding one of the first time periods to form a plurality of speed differences, and equating the speed differences.

The determining step may comprise performing the following calculation:

$$\theta_n = 360 / (1 + ((t_{1n} - t_{2n}) / (t_{1n} \cdot t_{2n})) \left(\sum_{i=1}^{i=N, i \neq n} (t_{1i} \cdot t_{2i}) / (t_{1i} - t_{2i}) \right))$$

where:

N is the number of markers on the rotary element;

θ_n is the nth angular spacing in degrees;

t_{1n} is the first time period corresponding to the nth angular spacing;

t_{2n} is the second time period corresponding to the nth angular spacing; and
 $n=1, 2, \dots, N$.

According to a second aspect of the invention, there is provided an apparatus for calibrating a rotary position transducer comprising a rotary element having a plurality of markers and a sensor cooperating with the rotary element to produce a position signal when each marker passes the sensor, the apparatus comprising means for measuring first time periods between consecutive position signals for a first revolution of the rotary element, means for measuring second time periods between consecutive position signals for a second revolution of the rotary element subsequent to the first revolution, and determining means for determining, when the rotary element is rotating with substantially constant deceleration, corrected angular spacings between the markers from the first and second time periods.

It is thus possible to provide a technique which allows teeth spacing to be calibrated on the basis of time period measurements without requiring any specific relative timings of the time periods. It is necessary for the time periods between tooth passages to be measured for two complete revolutions of the crankshaft and, provided the rotary element is rotated at a speed which decreases substantially linearly i.e. substantially constant deceleration, during the two revolutions, the time period measurements provide sufficient information to allow calibration of all of the angular spacings between teeth. Such calibration is not affected by "systematic" variations in speed of a cyclic nature. Further, this technique may be performed with an engine having any number of cylinders. Although calibration is required only once for each rotary position transducer, it may be performed repeatedly, for instance each time an internal combustion engine is operated in closed throttle fuel cut-off conditions of sufficient duration or once when such conditions occur during each time the engine is operated. Thus, if the rotary element has to be changed, the new element can be automatically recalibrated without requiring any operator intervention. The calibration as described above may be performed several times and an average calibration obtained.

The present invention will be further described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 illustrates diagrammatically a rotary position transducer;

Figure 2 illustrates an arrangement for performing a method constituting an embodiment of the invention;

Figure 3 is a graph of engine speed in revolutions per minute against time in seconds illustrating engine deceleration; and

Figure 4 is a graph illustrating the same data as in Figure 3 but plotted against engine revolutions as the horizontal axis.

The rotary position transducer shown in Figure 1 is intended for use with an internal combustion engine and comprises a toothed wheel 1 which is mounted on an engine crankshaft and which cooperates with a variable reluctance sensor 2. Teeth 3 to 6 are formed in the circumference of the wheel 1 and the passage of the teeth past the sensor 2 is detected. In particular, the output signal of the sensor 2 is processed by suitable electronic circuitry to determine the

passage of the leading edge of each tooth past the sensor 2.

As shown in Figure 1, the teeth 3 to 6 are nominally equi-angularly spaced about the axis of the wheel 1. Thus, the angular spacings θ_1 to θ_4 between consecutive pairs of teeth are nominally all equal to 90 degrees. However, manufacturing tolerances result in errors such that the actual angular spacings θ_1 to θ_4 differ from 90 degrees by respective angular errors Δ_1 to Δ_4 .

Figure 2 shows the wheel 1 mounted on the crankshaft 7 of an eight cylinder internal combustion engine 8. The sensor 2 is connected to an engine management system 9 which supplies control signals to the engine 8 for controlling the air/fuel ratio and quantity of mixture supplied to the cylinders of the engine 8 and the ignition timing of the engine. The engine management system 9 may be of any suitable type and many such systems are known. The engine management system 9 is further connected to a position transducer 10 which determines the position of an accelerator pedal 11 or throttle valve operated by a vehicle driver.

During normal operation of a vehicle, the driver produces an engine demand signal by operating the accelerator pedal 11. The position of the accelerator pedal 11, which corresponds to the driver demand, is determined by the position transducer 10 and supplied to the engine management system 9, which controls the ignition and fuelling of the engine 8 in accordance with the driver demand and other parameters, such as engine output speed, crankshaft position, engine temperature, etc.

The engine management system 9 is based on a microcontroller which is suitably programmed to perform engine management operation. The microcontroller is further programmed to perform calibration of the angular separations θ_1 to θ_4 of the teeth 3 to 6 on the wheel 1. It is thus possible to incorporate such calibration by providing appropriate additional software within the engine management system 9 so that no additional hardware is required.

In order to perform calibration of the position transducer, the engine management system 9 detects when the accelerator pedal 11 is at its normal rest position corresponding to zero driver demand and the engine is in a fuel cut-off condition. The engine management system performs the calibration provided the driver demand remains at zero for a sufficient number of revolutions of the engine crankshaft 7.

The engine management system 9 measures the time periods between the passage of consecutive ones of the teeth 3 to 6 for at least two complete revolutions of the crankshaft 7 with the engine 8 operating under closed throttle fuel cut-off conditions. The measured time periods are represented herein after by t_1 to t_8 . Figure 3 is a graph showing engine speed in revolutions per minute against time in seconds and shows the effect of closing the throttle and cutting off fuel at the two second point on the horizontal axis. The reduction in engine speed is non-linear i.e. deceleration with respect to time is not constant.

Figure 4 shows the same speed graph as Figure 3 but plotted against top dead centre (TDC) number on the horizontal axis, which corresponds to plotting engine speed against the number of engine revolutions. Following closing of the throttle and cutting off of the fuel, the engine speed reduces substantially linearly with respect to engine revolutions so that deceleration against engine revolutions is substantially constant. It is this phenomenon which is used in the present technique.

The actual average engine speeds ω_1 to ω_8 , for instance in degrees per microsecond, during the time intervals t_1 to t_n , respectively, are given by:

$$\omega_1 = (90 + \Delta_1)/t_1$$

$$\omega_2 = (90 + \Delta_2)/t_2$$

$$\omega_3 = (90 + \Delta_3)/t_3$$

$$\omega_4 = (90 + \Delta_4)/t_4$$

$$\omega_5 = (90 + \Delta_1)/t_1$$

$$\omega_6 = (90 + \Delta_2)/t_6$$

$$\omega_7 = (90 + \Delta_3)/t_7$$

EP 0 750 105 A1

$$\omega_8 = (90 + \Delta_4)/t_8$$

where Δ_i is the error, for instance in degrees, in tooth-to-tooth displacement for each i th sector on the timing wheel 1.
It is known that the sum of the actual sector angles is equal to 360 degrees so that:

$$(90 + \Delta_1) + (90 + \Delta_2) + (90 + \Delta_3) + (90 + \Delta_4) = 360.$$

As mentioned hereinbefore, this technique is based on the assumption, as illustrated in Figure 4, that deceleration over the two crankshaft revolutions during which the time intervals were measured is constant. Accordingly, deceleration measurements for each angular sector should be the same. In other words:

$$\omega_5 - \omega_1 = \omega_6 - \omega_2 = \omega_7 - \omega_3 = \omega_8 - \omega_4 = \text{Deceleration}$$

and:

$$(90 + \Delta_1)/t_5 - (90 + \Delta_1)/t_1 = \text{Deceleration}$$

$$(90 + \Delta_1) * (1/t_5 - 1/t_1) = \text{Deceleration and similarly:}$$

$$(90 + \Delta_2) * (1/t_6 - 1/t_2) = \text{Deceleration}$$

$$(90 + \Delta_3) * (1/t_7 - 1/t_3) = \text{Deceleration}$$

$$(90 + \Delta_4) * (1/t_8 - 1/t_4) = \text{Deceleration}$$

$(90 + \Delta_2)$, $(90 + \Delta_3)$ and $(90 + \Delta_4)$ can all be re-arranged in terms of $(90 + \Delta_1)$ as follows:-

$$(90 + \Delta_2) * (1/t_6 - 1/t_2) = (90 + \Delta_1) * (1/t_5 - 1/t_1)$$

$$(90 + \Delta_2) = [(90 + \Delta_1) * (1/t_5 - 1/t_1)] / (1/t_6 - 1/t_2)$$

$$(90 + \Delta_3) * (1/t_7 - 1/t_3) = (90 + \Delta_1) * (1/t_5 - 1/t_1)$$

$$(90 + \Delta_3) = [(90 + \Delta_1) * (1/t_5 - 1/t_1)] / (1/t_7 - 1/t_3)$$

$$(90 + \Delta_4) * (1/t_8 - 1/t_4) = (90 + \Delta_1) * (1/t_5 - 1/t_1)$$

$$(90 + \Delta_4) = [(90 + \Delta_1) * (1/t_5 - 1/t_1)] / (1/t_8 - 1/t_4)$$

Then using the relationship that

$$(90 + \Delta_1) + (90 + \Delta_2) + (90 + \Delta_3) + (90 + \Delta_4) = 360:$$

$$90 + \Delta_1 + \{[(90 + \Delta_1) \cdot (1/t_5 - 1/t_1)] / (1/t_6 - 1/t_2)\} + \{[(90 + \Delta_1) \cdot (1/t_5 - 1/t_1)] / (1/t_7 - 1/t_3)\} + \{[(90 + \Delta_1) \cdot (1/t_5 - 1/t_1)] / (1/t_8 - 1/t_4)\} = 360$$

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$$(90 + \Delta_1) \cdot (1 + (1/t_5 - 1/t_1) \cdot (1/(1/t_6 - 1/t_2) + 1/(1/t_7 - 1/t_3) + 1/(1/t_8 - 1/t_4))) = 360$$

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$$90 + \Delta_1 = 360 / (1 + (1/t_5 - 1/t_1) \cdot (1/(1/t_6 - 1/t_2) + 1/(1/t_7 - 1/t_3) + 1/(1/t_8 - 1/t_4)))$$

$$90 + \Delta_1 = 360 / [1 + ((t_1 - t_5) / (t_1 \cdot t_5)) \cdot ((t_2 \cdot t_6) / (t_2 - t_6) + (t_3 \cdot t_7) / (t_3 - t_7) + (t_4 \cdot t_8) / (t_4 - t_8))]$$

15 Similarly by repeating the calculation above for the other sectors:-

$$90 + \Delta_2 = 360 / [1 + ((t_2 - t_6) / (t_2 \cdot t_6)) \cdot ((t_1 \cdot t_5) / (t_1 - t_5) + (t_3 \cdot t_7) / (t_3 - t_7) + (t_4 \cdot t_8) / (t_4 - t_8))]$$

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$$90 + \Delta_3 = 360 / [1 + ((t_3 - t_7) / (t_3 \cdot t_7)) \cdot ((t_1 \cdot t_5) / (t_1 - t_5) + (t_2 \cdot t_6) / (t_2 - t_6) + (t_4 \cdot t_8) / (t_4 - t_8))]$$

$$90 + \Delta_4 = 360 / [1 + ((t_4 - t_8) / (t_4 \cdot t_8)) \cdot ((t_1 \cdot t_5) / (t_1 - t_5) + (t_2 \cdot t_6) / (t_2 - t_6) + (t_3 \cdot t_7) / (t_3 - t_7))].$$

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It is thus possible to determine the actual angular spacings $(90 + \Delta_1)$ to $(90 + \Delta_4)$ purely on the basis of inter-tooth time intervals measured during two complete rotations of the wheel 1. The technique relies on the fact that the sum of the spacings must be equal to 360 degrees. The technique further relies on the deceleration occurring between the first and second time interval measurement for each sector being equal. The time interval measurements need not be taken during consecutive crankshaft revolutions, although this may be convenient. Further, several calibration processes may be performed and the results averaged so as to reduce the effects, for instance, of essentially random fluctuations.

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The technique may be performed at any time during conditions of overrun i.e. closed throttle fuel cut-off operation of the engine, preferably with the engine disconnected from the road wheels by a transmission system. Although calibration of the wheel is required only once and with the engine disconnected from the road wheels by a transmission system. Although calibration of the wheel is required only once and need not be repeated unless the existing wheel is replaced by a new wheel, it may be convenient to perform the calibration once after each time the engine is operated.

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Calibration is not affected by cyclic variations in crankshaft speed. Thus, it is possible to provide an accurate and robust technique for calibrating angular spacing errors in rotary position transducers.

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Claims

1. A method of calibrating a rotary position transducer comprising a rotary element (1) having a plurality of markers (3, 4, 5, 6) and a sensor (2) cooperating with the rotary element (1) to produce a position signal when each marker (3, 4, 5, 6) passes the sensor (2), comprising the steps of:

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rotating the rotary element (1) with substantially constant deceleration;
measuring first time periods between consecutive position signals for a first revolution of the rotary element (1);
measuring second time periods between consecutive position signals for a second revolution of the rotary element (1) subsequent to the first revolution; and
determining corrected angular spacings between the markers (3, 4, 5, 6) from the first and second time periods.

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2. A method as claimed in Claim 1, characterised in that first and second revolutions are consecutive revolutions.

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3. A method as claimed in Claim 1 or 2, characterised in that the determining step comprises calculating average speeds during the first and second time periods, subtracting the average speed for each of the second time periods from the average speed for the corresponding one of the first time periods to form a plurality of speed differences,

and equating the speed differences.

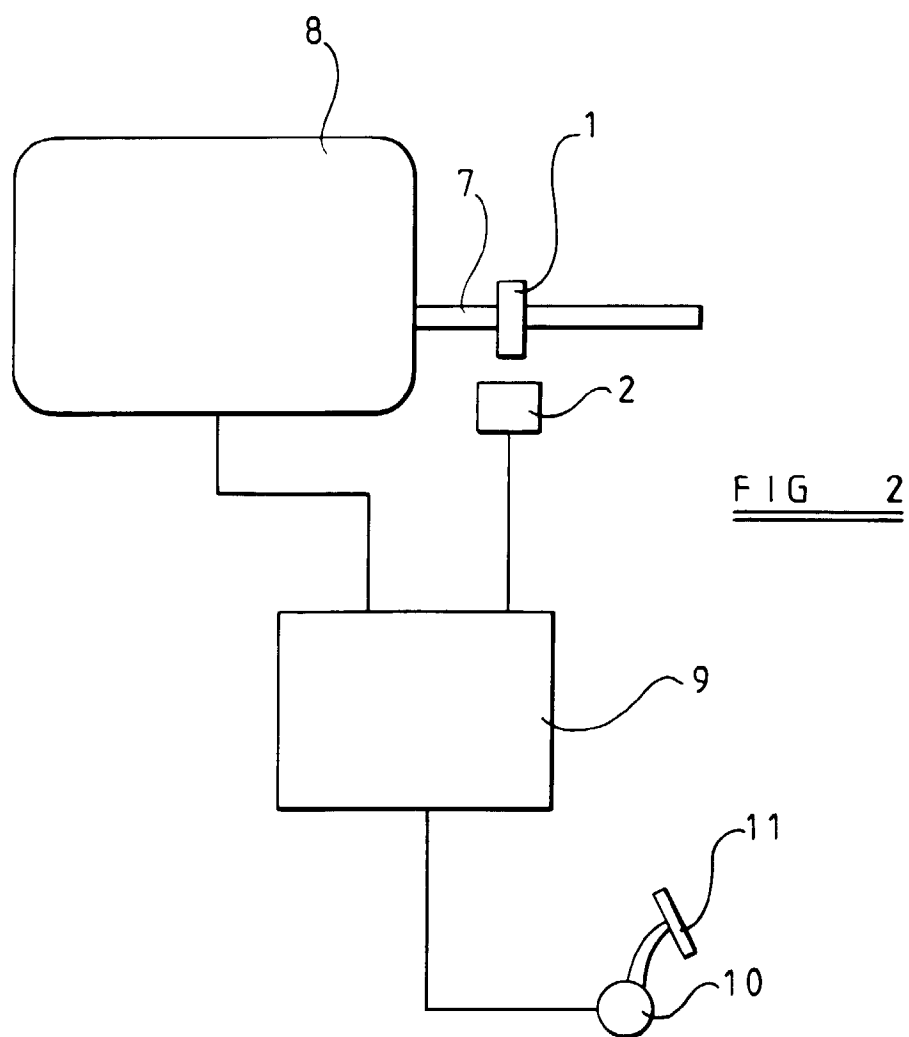
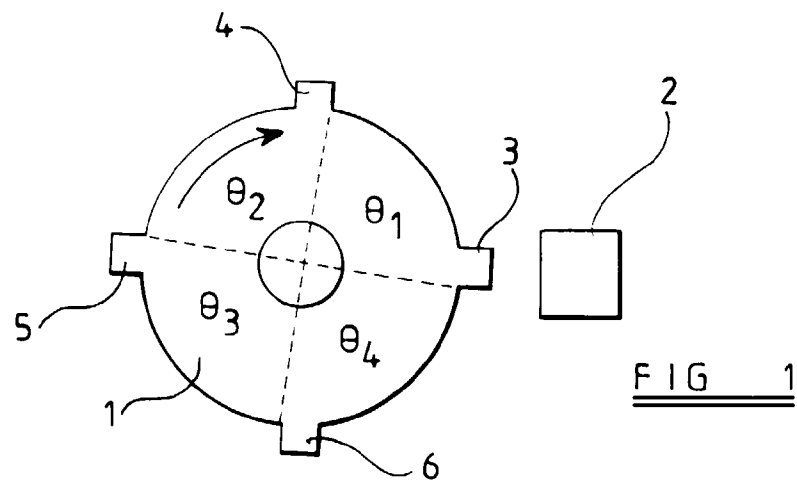
4. A method as claimed in any one of the preceding claims, characterised in that the determining step comprises calculating the angular spacing θ_n between consecutive markers (3, 4, 5, 6) as:

$$\theta_n = X / (1 + ((t_{1n} - t_{2n}) / (t_{1n} \cdot t_{2n})) (\sum_{i=1}^{i=N, i \neq n} (t_{1i} \cdot t_{2i}) / (t_{1i} - t_{2i})))$$

where:

N is the number of markers (3, 4, 5, 6) on the rotary element (1);
 t_{1n} is the first time period corresponding to the nth angular spacing θ_n ;
 t_{2n} is the second time period corresponding to the nth angular spacing θ_n ;
 $n = 1, 2, \dots, N$; and
 X is an angular measure of a single revolution.

5. A method as claimed in any one of the preceding claims, characterised in that the markers (3, 4, 5, 6) are nominally equi-angularly spaced.
6. A method as claimed in any one of the preceding claims, characterised in that the rotary element comprises a toothed wheel (1).
7. A method as claimed in Claim 6, characterised in that the sensor comprises a variable reluctance sensor (2).
8. A method as claimed in any one of the preceding claims, characterised in that the rotary element (1) is driven by an internal combustion engine (8) under closed throttle fuel cut-off conditions.
9. A method as claimed in Claim 8, characterised in that the number of markers (3, 4, 5, 6) is equal to the number of firing events per revolution of an engine crankshaft.
10. An apparatus for calibrating a rotary position transducer comprising a rotary element (1) having a plurality of markers (3, 4, 5, 6) and a sensor (2) cooperating with the rotary element (1) to produce a position signal when each marker (3, 4, 5, 6) passes the sensor (2), characterised in that the apparatus comprises means for measuring first time periods between consecutive position signals for a first revolution of the rotary element (1) means for measuring second time periods between consecutive position signals for a second revolution of the rotary element (1) subsequent to the first revolution, and determining means for determining, when the rotary element (1) is rotating with substantially constant deceleration, corrected angular spacings between the markers (3, 4, 5, 6) from the first and second time periods.
11. An apparatus as claimed in Claim 10 for a rotary position transducer of an internal combustion engine (8), characterised by being embodied within an engine management system (9) of the engine (8).



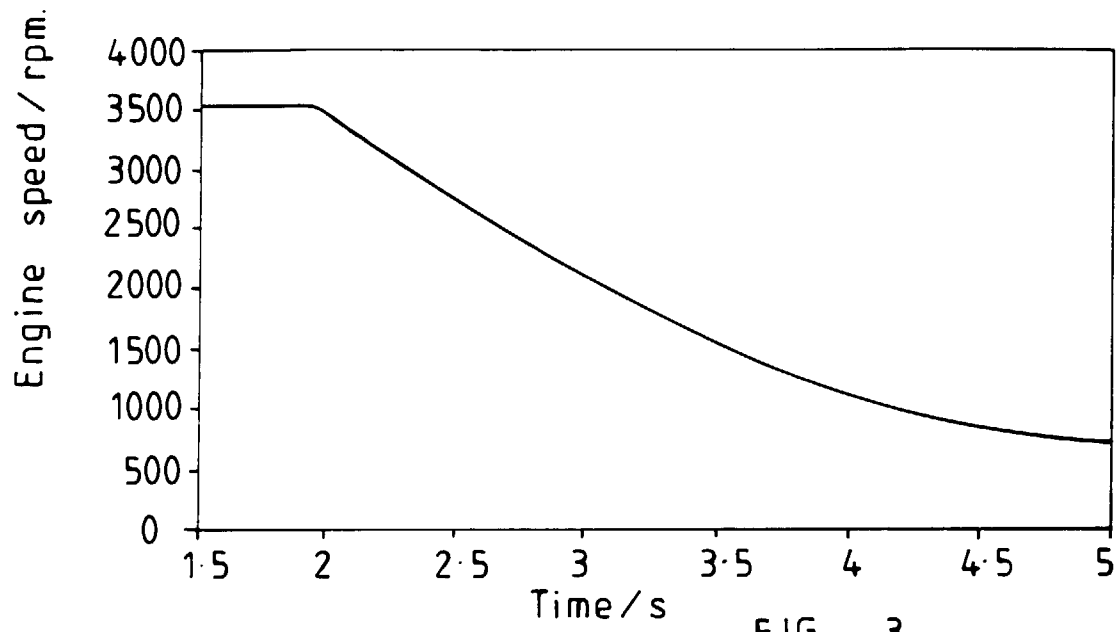


FIG 3

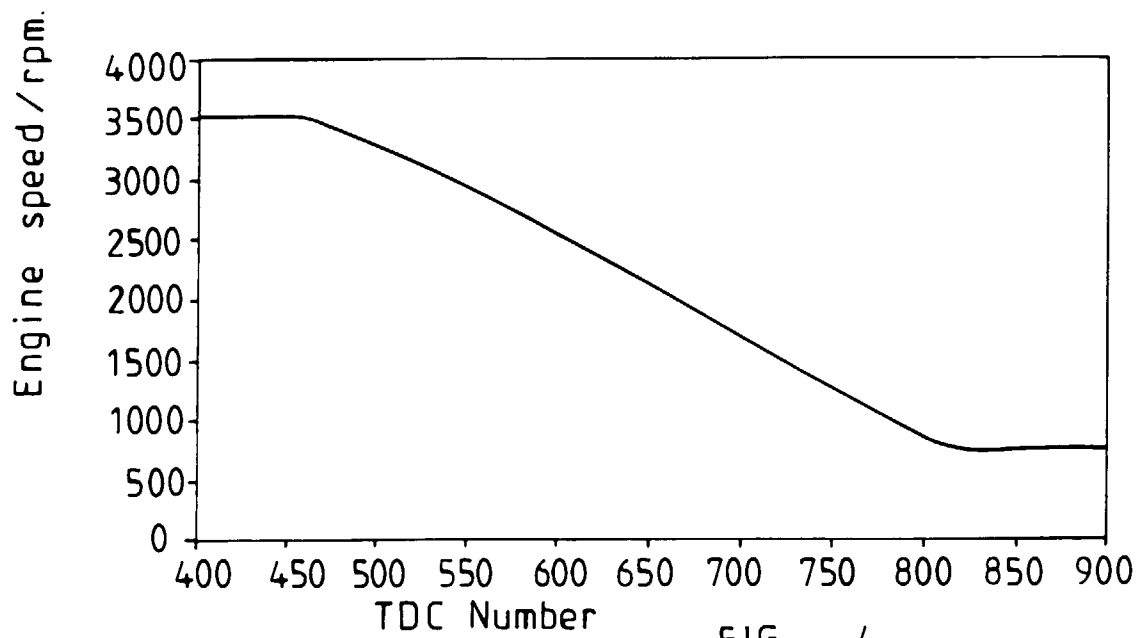


FIG 4



European Patent
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EUROPEAN SEARCH REPORT

Application Number
EP 96 30 3794

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
Y	WO 93 07497 A (BOSCH GMBH ROBERT ;AUDI NSU AUTO UNION AG (DE)) 15 April 1993 * page 4, paragraph 3 - page 7, paragraph 3; figures 1-3 *	1,2,5-11	F02D41/34
A	---	3,4	
D,Y	US 5 117 681 A (DOSDALL JAMES M ET AL) 2 June 1992 * column 4, line 6 - column 5, line 40; figures 4-6 *	1,2,5-11	
A	-----	3,4	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			F02D
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 23 September 1996	Examiner Chapple, I
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