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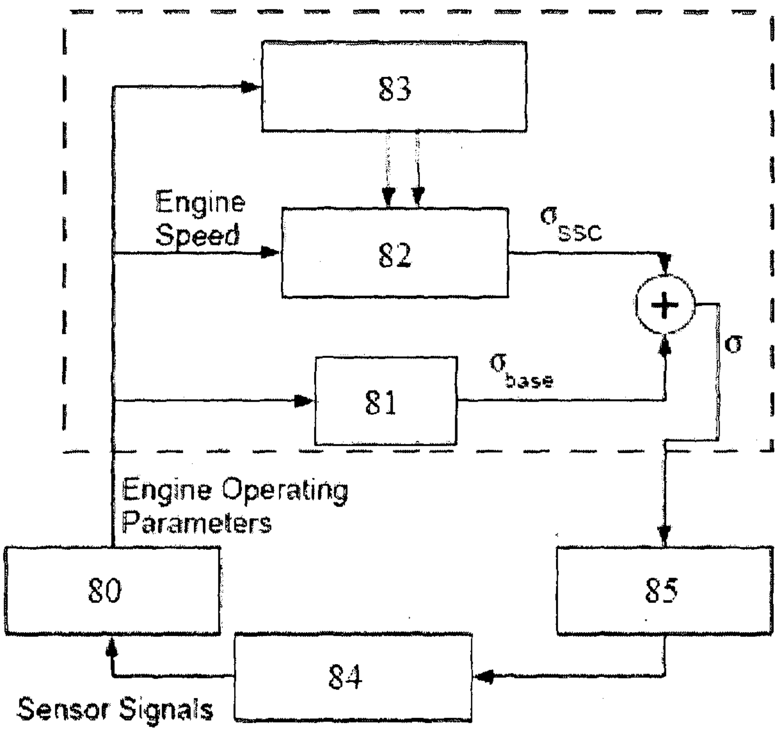
(54) Title: A SYSTEM AND METHOD FOR CONTROLLING THE IGNITION TIMING OF AN INTERNAL COMBUSTION ENGINE



(57) Abstract: A system and method of calculating ignition timing of a spark-ignited internal combustion engine that results in optimal operation of engine while ensuring suitable knock margin is provided. A base ignition timing σ_{base} is calculated using engine operating parameters, an additional ignition timing σ_{ssc} is calculated using an adaptive slope-seeking controller and a resultant ignition timing is calculated using the two calculated ignition timings. The operation of the slope-seeking controller (82) is controlled based on engine operating conditions.

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TITLE OF THE INVENTION

A system and method for controlling the ignition timing of an internal combustion engine

FIELD OF THE INVENTION

The present invention relates a system and method for controlling ignition timing of an internal combustion (IC) engine. Particularly, it relates to a system and method for controlling ignition timing of a spark-ignited internal combustion engine that results in optimal operation of engine while ensuring suitable knock margin.

BACKGROUND OF THE INVENTION

Spark-ignited IC engines are widely used as prime movers for applications such as transport and power generation. These engines convert chemical energy stored in a fuel such as gasoline into useful mechanical work. Control of spark-ignited IC engines has been an active area of research for many decades.

For spark-ignited IC engines, the ignition timing, that is the precise time at which a spark event that triggers combustion occurs, is an important control parameter that governs the efficiency of engine operation. For optimal engine operation, the ignition timing needs to be accurately controlled and varied suitably in response to engine operating conditions such as engine speed, load and engine temperature. The most prevalent method of controlling spark-ignited IC engines in practice is to use a set of sensors for interpreting engine operating conditions, and choose ignition timing based on such interpreted engine operating conditions using a pre-calibrated table stored in an electronic control unit that controls the ignition timing. The table stored in memory of the electronic control unit is constructed using a set of calibration experiments on a set of sample engines that are representative of engines on which such ignition system is to be deployed. This method has a drawback, namely that it does not account for variations in engine characteristics arising due to factors such as manufacturing variations, ageing of engine components and change in fuel quality. Due to the presence of such variations in engine characteristics, the ignition timing calculated using a pre-calibrated table may not lead to an optimal engine operation.

Methods of choosing ignition timing in real-time using a sensor for detecting engine knock have been described, for example, in following patents: U.S. Pat. No. 4,445,479, U.S. Pat. No. 5,144,928 and U.S. Pat. No. 4,583,175. Such schemes provide a potential for more optimal engine operation, but at an expense of added cost of sensor and related circuitry.

The present techniques used in an IC Engine are briefly described with reference to the following description and the accompanying drawings, wherein the same characters and numerals denote the same parts and wherein,

Figure 1 is a schematic illustration of an internal combustion engine, to which embodiments of the present technique are applicable;

Figure 2 is a graphical representation of the variation in torque generated by an IC engine with respect to the ignition timing for a set of operating conditions;

Figure 3 is a graphical representation of the variation in torque generated by an IC engine with respect to the ignition timing for an operating condition that shows the knocking region;

Figure 4 is a schematic representation of the ESC method;

Figure 5 is a graphical representation that shows reduction in knock margin that results when ESC method is used for ignition timing control application;

Figure 6 is a schematic representation of the Slope Seeking Control (SSC) method;

Figure 7 is a graphical representation that shows how knock margin can be adjusted using different target slope values when SSC method is used for ignition timing control of spark-ignited IC engines;

Figure 1 is a schematic illustration of one cylinder of a four-stroke spark-ignited internal combustion engine. It should be understood that a four-stroke internal combustion engine configuration has been illustrated for the purpose of description only. The system and the method described in this invention are equally applicable to two-stroke spark-ignited internal combustion engines. Returning to Figure 1, when the intake valve **1** opens, a mixture of air and fuel enters the cylinder **2**. The mixture is ignited by a spark initiated by the spark plug **3**. The resulting explosive combustion drives the piston **4** downwards as viewed in Figure 1, rotating the crankshaft (not shown in Figure). When the exhaust valve **5** opens, the exhaust gases generated during combustion leave the cylinder. Thus the explosive combustion of a mixture of air and fuel leads to generation of mechanical torque. The torque is subsequently transferred to the output shaft which is connected to load through appropriate transmission system. For example, in an automobile, output shaft is connected to wheels through a transmission. In a generator set, the output shaft is connected to the shaft of an alternator through a transmission system.

The precise timing at which the spark is initiated by the spark plug **3** is controlled by an Electronic Control Unit (ECU) **6**. The ECU **6** comprises of an input interface **6a** for processing of sensor signals, a CPU **6b**, memory **6c** and driver circuitry **6d** to drive the ignition coil that energizes the spark plug. The ECU processes signals generated by multiple sensors such as engine speed sensor 7, wheel speed sensor **8**, throttle position sensor **9**, cylinder head temperature sensor **10,** takes decision on when to actuate the spark and energizes the spark plug accordingly though the driving circuitry.

The torque generated by the engine is strongly influenced by the ignition timing. The variation in torque generated as a function of the ignition timing, in terms of degrees before top-dead-center, corresponding to a set of engine operating conditions is graphically represented in Figure 2. Engine operating conditions can be characterized in terms of parameters such as engine speed, throttle opening and engine oil temperature. As shown in Figure, the torque generated by the engine has an extremum relationship with respect to the ignition timing. Specifically, for a given engine operating condition, the torque is maximum for a specific value of the ignition timing. Also, as seen from the figure, the ignition timing that maximizes the torque generated by the engine varies with variation in engine operating conditions. Hence, for optimal operating of the engine, the ignition timing must be varied as a function of the engine operating conditions.

Figure 3 shows the engine torque as a function of ignition timing for an engine operating condition. As mentioned previously, engine output torque is maximum for a specific value of ignition timing. However, if ignition timing is increased beyond a certain value, a phenomenon known as engine knocking occurs. This phenomenon is extremely detrimental to life of the engine, and is highly undesirable. For a given engine operating condition, the difference between executed ignition timing and the ignition timing at which the engine knocking starts appearing is known as knock margin. In a spark-ignited IC engine, it is desirable that there is sufficient knock margin available under all engine operating conditions.

For certain engine operating conditions such as high load conditions, ignition timing at which knock starts appearing is close to the ignition timing that leads to maximum engine torque. Under such conditions, if ignition timing is chosen to be the timing that results in maximum engine torque, the knock margin is greatly reduced. In certain extreme conditions, ignition timing at which knock starts appearing can be less that the ignition timing at which the torque is maximum. Thus, it is not always desirable to operate the engine at the ignition timing that results in maximum torque output. This also indicates that there is a trade-off between engine output torque and knock margin. Further, the ignition timing at which knock starts appearing is a function of engine operating conditions such as cylinder head temperature and atmospheric pressure. Considering these factors, in most practical applications ignition timing is chosen to be less that the ignition timing that results in maximum output torque to provide sufficient knock margin.

In many practical applications that utilize spark-ignited IC engines, the common method of choosing the ignition timing corresponding to a given engine operating condition involves carrying out a number of calibration tests on a set of sample engines. From such calibration tests, the optimal value of the ignition timing corresponding to various engine conditions that lead to an appropriate trade-off between engine output torque and knock margin are determined and stored in the memory of the ECU in the form of a table. During actual operation, the engine operating conditions are determined by the ECU using one or more sensors. The stored value of the ignition timing corresponding to the measured engine conditions is then retrieved from memory and used.

However, due to several factors such as manufacturing variations, aging, change in fuel quality, undetected changes in engine operating conditions, using an ignition timing that was found from the calibration exercise may not lead to an optimal operation of the engine. The engine may operate with either too retarded ignition timing which results in engine torque output to be considerably lower than the maximum possible engine torque, or with too advanced timing which results in poor knock margins or in extreme case in knocking of engine. Thus, a scheme that decides, in real-time, the optimal ignition timing corresponding to the given engine operating conditions is highly desirable.

A method of finding ignition timing that is sometimes used in practice involves using a dedicated sensor for determining onset of engine knock. In this method, during operation of engine, ignition timing is increased till the output of knock sensor indicates onset of engine knock. When such a condition is detected, advance of ignition timing is stopped. This method can lead to more optimal engine operation as compared to more widely used method of determining ignition timing using calibration experiments, but it requires a dedicated sensor, additional circuitry and additional computational power for processing the sensor output. This may not be economically feasible in application such as small two-three wheeler vehicles, small cars and generator sets.

Extremum Seeking Control (ESC) is a technique described in *"Real-Time Optimization by Extremum-Seeking Control" M. Krstic and K. B. Ariyur, Wiley Interscience, 2003*, for real-time optimal control of a system. The technique is applicable to a type of systems where the relationship between the systems inputs and outputs exhibits an extremum characteristic. Applications of ESC for different types of systems, including ignition timing control of spark-ignited IC engines have been proposed in following patents: U.S. Pat. No. 7,457,619, U.S. Pat. No. 6,098,010, U.S. Pat. No. 6,522,991, U.S. Pat. App. No. US2010/0106328 and U.S. Pat. No. 7,698,051. A schematic representation of the methodology is shown in Figure 4. As shown in the figure, Plant **20** is a system being controlled, which exhibits an extremum relationship between input u and output y. The ESC method consists of passing the output y of the controlled plant **20** through a washout filter **21** (i.e. a high-pass filter), multiplying the output w of the washout filter **21** with a periodic perturbation signal m and integrating the product d. The input u to the plant is chosen as the scaled **23** version of output of the integrator **22** added together with the periodic perturbation signal m. It can be shown that in steady-state, the mean value of input u corresponds to the input value that leads to an extremum value of output y. Methods of using ESC have been proposed for many practical applications such as HVAC control, information network control and control of mechanical compressors. Additionally, methods based on ESC have been proposed in relation to IC engine control, for conducting engine calibration experiments, and for real-time control.

Figure 5 shows engine output torque as a function of ignition timing for an engine operating condition. Since relationship between ignition timing and output torque exhibits extremum characteristic, ESC technique can be applied for control of ignition timing such that output torque is maximized. Using ESC method in such a manner will result in execution of the ignition timing that result in maximum engine torque. However, as mentioned previously, in most operating conditions, choosing an ignition timing that results in maximum torque output results in poor knock margins, or in extreme cases in engine knocking, which is a highly undesirable phenomenon that reduces life of the engine. Thus, ESC is not suitable for control of ignition timing of spark-ignited IC engines.

The Slope Seeking Control (SSC) technique, described in *"Slope-Seeking, a Generalization of Extremum Seeking" International Journal of Adaptive Control and Signal Processing, 2004, 18:1-14*, is a generalization of the ESC technique that is applicable to systems that have an extremum relationship between inputs and outputs. The SSC technique provides means of attaining a certain slope of the input-output relationship, rather than the extremum point which is attained by the ESC method. A schematic representation of the SSC method is shown in Figure 6. As shown in the Figure, the SSC method is similar to the ESC method with one major difference: the input to the integrator **22** is the signal d added with a suitably chosen offset o. This results in a choice of the system input that attains a target slope on the input-output relationship.

Figure 7 shows how SSC method can be suitably applied for ignition timing control of spark-ignited IC engines. As mentioned previously, SSC method allows for attaining a specified slope of the input-output relationship. Referring to Figure 7, it can be seen that by keeping different values of target slope, knock margin can be suitable chosen. As shows in Figure 7, application of SSC control with target slope value of Target Slope 1 results in ignition timing σ_1. Similarly, application of SSC control with target slope value of Target Slope 2 results in ignition timing σ_2. Thus, it is possible to choose a knock margin by suitably choosing a target slope value. This flexibility is not provided by the ESC method. Hence, SSC method is more suitable for real-time control of ignition timing as compared to the ESC method.

Although SSC method allows for choosing an optimal ignition timing while incorporating desired knock margin, it is not useful under all operating conditions seen in a practical application of an internal combustion engine such as a vehicle or a generator set. Under certain operating conditions such as engine idling and fast changes in engine speed, it is not necessary or even desirable to use the SSC method. For example, using the SSC method during engine idling may lead to unstable engine operation, which is undesirable. Thus, a practical method of ignition timing control that utilizes the SSC method requires a selective use of the SSC method under suitable engine operating conditions. Further, for optimal operation, the parameters used in SSC method may also need to be changed depending on engine operating conditions. A single set of parameters for the SSC method may not work under all operating conditions.

OBJECTIVES OF THE INVENTION

An objective of the invention is to provide a system and method for controlling the ignition timing of a spark-ignited IC Engine which obviates the aforesaid drawbacks.

DESCRIPTION OF THE INVENTION

In order to achieve the aforesaid and other objectives, according to the invention, a system and method of calculating ignition timing of an IC Engine is disclosed. Base ignition timing is calculated using engine operating parameters, an additional ignition timing is calculated using an adaptive slope-seeking controller and a resultant ignition timing is calculated using the two calculated ignition timings. The operation of the slope-seeking controller is controlled based on engine operating conditions.

These and other aspects, features and advantages of the invention will be better understood with reference to the following description and the accompanying drawings, wherein the same characters and numerals denote the same parts and wherein,

Figure 8 is a schematic representation of a method for determining, in real time, ignition timing of a spark-ignition IC engine;

Figure 9 is a schematic representation of the internal operation of the Slope Seeking Controller block shown in Figure 8;

Figure 10 is an exemplary flowchart illustrating the method used in SSC Control Parameter and Reset Control block of the method described in Figure 8;

Figure 11 is a schematic representation of an experimental setup that can be used for determination of parameters o and K;

Figure 12 is an illustration of relationship between engine torque, experimentally computed quantity μ and ignition timing;

Figure 13 is an exemplary flowchart illustrating the method used in a part of the method described in Figure 8, where engine speed is considered to be the only input available for computation of ignition timing;

Figure 14 is a schematic representation of a system that implements real-time control of ignition timing for a spark-ignited IC engine using method described in this invention; and

Figure 15 is a schematic representation of the method implemented in microcontroller shown in Figure 14.

Figure 8 describes schematically, a method for determining, in real-time, ignition timing of a spark-ignited IC engine. It is assumed that the ignition timing σ determined by the method is executed in an IC engine **84** through suitable means **85**, and that output of a set of sensors that monitor engine operating parameters is processed through a sensor processing block **80** and is available as an input. It is assumed that engine speed is one of the outputs of the sensor processor block **80**. As seen from Figure 8, the method consists of three blocks: a Lookup Table block **81** that takes in engine speed, possibly along with other processed engine operating parameters such as throttle opening, engine oil temperature and manifold absolute pressure, and determines a base value of ignition timing, called σ_{base}; a Slope Seeking Controller block **82** that implements a type of slope-seeking controller and a block **83** for controlling parameters and operation of Slope Seeking Controller block **82**, called SSC Parameter and Reset Control. Operation of each block will subsequently be explained in detail.

The Lookup Table block **81** implements a table lookup operation, where based on a set of processed sensor values that indicate engine operating conditions, an ignition timing value is retrieved from a pre-calibrated table. Several possibilities exist regarding size and number of inputs of the lookup table. As an example, the table may have engine speed and throttle openings as inputs. Alternatively, the table may have only engine speed as an input. Ignition timing values as a function of the inputs are determined in advance, and are stored in the lookup table. When engine is running, a value of ignition timing corresponding to the inputs to the table is retrieved. Suitable interpolation operations may also be performed on the retrieved values. The output of the block is a base value of ignition timing, called σ_{base}.

Figure 9 shows a schematic representation of the internals of the Slope Seeking Controller block. The block **82** takes engine speed as an input, and gives an ignition timing value, called σ_{SSC} as output. As shown in Figure, engine speed is passed through a high-pass filter (HPF) **90** to generate signal x1, which is multiplied by a signal x2 to generate signal x3. Signal x2 is a phase-delayed version of a periodic perturbation signal m, delayed by a phase Δ. In accordance with a target slope, an offset o is subtracted from signal x3 to generate signal x4. Signal x4 is passed through an integrator **91** to generate signal x5. Signal x5 is scaled by the Scaling block **92** by a factor K to generate signal x6. Signal x6 is passed through a Saturation block **93** that restricts value of signal x6 between two pre-defined limits to generate signal x7. Signal x7 is added with the periodic perturbation signal m to generate the output σ_{SSC} of the block **82**. The value stored in integrator **91** can be reset, that is set to be equal to zero, using a Reset Command signal **94**. The Reset Command signal **94** is generated by the SSC Parameter and Reset Control block **83**. The operation of the Slope Seeking Control block **82** can be characterized by parameters K, Δ and o. These parameters as well as overall operation of the block is controlled by the SSC Parameter and Reset Control block **83**.

SSC Parameter and Reset Control block **83** governs the operation of the Slope Seeking Control block **82**. The block **83** takes in a set of engine operating parameters as inputs. Broadly, it performs the following functions: it decides the parameters K, Δ and o of the Slope Seeking Control block **82**; it decides whether the Slope Seeking Control block **82** needs to be executed and it decides when to reset the integrator **91** used in Slope Seeking Control block **82**. A flow-chart representation of the operation of the block is shown in Figure 10. It is assumed that the sequence of operations defined in the flow-chart is repeated periodically. In the first step (S01), engine operating condition is determined based on values of engine operating parameters. Determination of engine operating condition is required, since in certain engine operating conditions, it may not be necessary, or even desirable to execute the Slope Seeking Control block. Examples of such conditions are engine idling, rapid accelerations/decelerations and transmission ratio shifts in automobiles equipped with stepped transmission. It needs to be ensured that under such conditions, the Slope Seeking Control block is not executed. Referring to Figure 10, based on operating condition of the engine, in step S02 it is decided whether to execute computations related to the Slope Seeking Control block. If it is decided that the computations related to the Slope Seeking Control block are not to be executed, then in step S03 integrator used in Slope Seeking Control block is reset, and value of σSSC is set to zero. Alternatively, if it is decided in step S02 that the computations related to Slope Seeking Control block are to be executed, then in step S04 vlaues of parameters K, Δ and o are determined based on values of engine operating parameters. These parameters are then used in computations performed in Slope Seeking Control block.

SSC Parameter and Reset Control block contains values of parameters K, Δ and o stored as a function of engine operating parameters. A description of how to choose these values as a function of engine operating parameters will now be provided.

Parameter Δ is required to account for the phase shift between modulation input (ignition timing) and engine speed at modulation frequency. Since the system from ignition timing input to engine speed output is dynamic in nature, the output corresponding to the modulation input will be shifted from modulation input by a few degrees. It is necessary to account for this phase shift appropriately, since a wrong choice of phase shift compensation can lead to slow convergence to optimal ignition timing, or in extreme case in instability of system. Specifically, a sufficient condition to ensure stability of system is that the resulting phase difference between the demodulation signal (x2 in Figure 9) and engine speed is less than 90 deg. The phase shift between modulation input and corresponding output is a function of the modulation frequency, and of the frequency response characteristics of the input-output system. When the dynamics corresponding to the IC engine system are fixed in nature, for example as in a generator set, the amount of this phase shift is fixed with respect to the engine operating parameters. During implementation, this fixed value of phase shift, which can be computed a-priori based on knowledge of system dynamics, can be used. On the other hand, when the dynamics of the IC engine system are a function of engine operating conditions, this phase shift can be a function of engine operating parameters. An example of this kind is an automobile with multi-stepped transmission, where the dynamics are a function of the transmission ratio. In this case, during implementation, the parameter Δ can be chosen based on engine operating parameters. The value of parameter Δ to be used in run-time can be found out a-priori based on knowledge of dynamics of the system. In the special case where the system dynamics are a function of engine operating conditions, but it is not possible to identify the relevant operating condition in run-time, for example due to lack of relevant sensors, a fixed value of 45 degrees can be used for parameter Δ. This is because the dynamic relationship between a change in ignition timing and a change in engine speed can be well-approximated by a first-order linear system, and it is well-known that for such a system, irrespective of the system parameters, the phase difference between the input and output is always between 0 degree and 90 degrees. Thus, when the parameter Δ is chosen to be 45 degrees, it is ensured that the phase difference between the demodulation signal and the engine speed component corresponding to modulation is less than or equal to 45 degrees, which is a sufficient condition for system stability. Thus, setting value of parameter Δ to 45 degrees ensures stable system operation in presence of changing system dynamics even when relevant operating conditions cannot be detected.

Choice of parameter "o" decides the target slope between the torque and ignition timing, which in turn decides the knock margin. Parameter "o" can be chosen by conducting controlled experiment on the target engine system. A schematic diagram of the experimental setup that can be used for this purpose is shown in Figure 11. As shown in the figure, the experimental setup consists of means of varying load on engine to maintain the speed of engine at a constant level, means of executing ignition timing at desired level, where ignition timing consists of a freely settable mean value with a freely settable modulation component added to it, and means of computing a quantity μ based on measured engine speed and modulation part of ignition timing. The calculated value of μ corresponds to the slope of relationship between engine torque and ignition timing. By conducting experiments at different constant speeds and different constant throttle openings, the value of μ for different values of ignition timing can be calculated. An illustration of relationship between engine torque, value of μ and mean ignition timing for a constant engine speed for two different throttle openings is shown in Figure 12. As seen from the Figure, the value of parameter "o" can be chosen from such observed relationship as the value of μ that leads to an acceptable lowering of engine torque. The value of parameter "o" can thus be calibrated for a combination of engine speeds and throttle opening values, and stored in a table during run-time implementation. Alternatively, it can be observed from Figure 12 that for constant engine speed, for a given distance from the ignition timing that corresponds to the maximum torque, value of μ is lesser for higher throttle opening. Thus, for a given engine speed, choosing the value of "o" that corresponds to an acceptable lowering of engine torque for highest throttle opening will lead to acceptable lowering of engine torque at any lower throttle opening. This characteristic can be used in implementations where the throttle position sensor is not available, where the value of parameter "o" can be derived for highest throttle openings for a set of engine speeds, and stored as a function of engine speed alone. During run-time, the value of parameter "o" can be retrieved using the prevalent engine speed.

Value of parameter K decides the rate of convergence of ignition timing to the target ignition timing value. Value of parameter K can also be found from experiments conducted for determining values of parameter "o". Specifically, referring to Figure 12, value of parameter K, and the difference (μ - o) decides the system convergence rate. Since μ and o are known, value of K can be chosen to be the value that will lead to an acceptable rate of convergence. A set of values of K can thus be determined as a function of engine speed and throttle positions. During implementation, based on prevalent values of engine speed and throttle position, the value of K can be selected from a stored table. Further, similar to choice of parameter "o", for a given engine speed, value of difference (μ - o) is lowest for highest throttle opening. Consequently, if the value of K derived for highest throttle opening is used for a lower throttle opening, the convergence rate will be better than the convergence rate at highest throttle opening. This characteristic can be used in implementations where the throttle position sensor is not available, where the value of parameter K can be derived for highest throttle openings for a set of engine speeds, and stored as a function of engine speed alone. During run-time, the value of parameter K can be retrieved using the prevalent engine speed.

Method described in Figure 8 enables optimal operation of a spark-ignited IC engine while preserving a suitable knock margin. It addresses variations in engine characteristics arising due to factors such as aging, change in fuel quality and manufacturing variations by suitable changing ignition timing in real-time operation. The method also prevents undesirable ignition timing changes that may occur in SSC technique when engine is undergoing fast changes in operating conditions. Further, optimization of ignition timing is not performed under conditions where such optimization is not required, such as during engine idling.

An embodiment of the method described above will now be presented. In this embodiment, engine speed is considered to be the only available Engine Operating Parameter input for computation of ignition timing. In this embodiment, the Lookup Table block (shown in Figure 8) consists of a one dimensional lookup table that specifies the base ignition timing σ_{base} as a function of engine speed. The Slope Seeking Control block remains identical to one shown in Figure 9. A flow-chart representation of the SSC Parameter and Reset Control block is shown in Figure 13. As shown in Figure 13, the first step S01 of the SSC Parameter and Reset Control block is to check whether the engine speed (denoted as RPM in Figure 13) is less than a predetermined value, called RPM_{idle}. If this condition is found to be true, then it is concluded that engine is under idling conditions. Accordingly, in step S04 the integrator used in the Slope Seeking Control block is reset, and ignition timing σ_{SSC} is set to zero. In step S01, if engine speed is found to be higher than the predetermined engine speed RPM_{idle}, then in step S02 the time derivative of engine speed, dRPM, is calculated. In step S03, it is checked whether absolute value of dRPM is higher than a predetermined value, $dRPM_{limit}$. If this condition is found to be true, then it is concluded that fast transients in engine operation is taking place. Accordingly, step S04 is executed as mentioned earlier. If in step S03, absolute value of dRPM is found to be less than the predetermined value $dRPM_{limit}$, then in step S05 the Slope Seeking Control block parameters K, Δ and o are computed as functions of engine speed.

Using the method described in above embodiment, an optimal ignition timing for a spark-ignited IC engine can be calculated using only engine speed as input.

Figure 14 describes a system that implements real-time optimal control of ignition timing of a spark-ignited IC engine using the method described in this invention. As shown in Figure, there are three main components of the system **140**. The first component is a signal processing circuitry **141** that interfaces with a set of available sensors, and generates signals that can be accepted by a microcontroller **142**. The second component is a microcontroller **142** accepts the signals generated by the signal conditioning circuitry, executes the method and generates command signals for the ignition driver circuitry **143**. The third component is an ignition driver circuitry **143** that energizes the ignition coil to generate spark in IC engine in response to commands received from the microcontroller **142**.

Figure 15 describes schematically the method executed by the microcontroller shown in Figure 14. The first part of the method reads the sensor signals processed by the signal conditioning circuitry **150** and generates signals representing engine operating parameter **152** that are used by the ignition timing calculation block **151**. The optimal ignition timing calculation block **151** contains the method that performs computations according to the method described in Figure 8 to calculate optimal ignition timing σ. The timing computation block **153** takes the ignition timing σ and a processed sensor signal corresponding to crankshaft position as inputs. Based on ignition timing to be executed, and using crankshaft position as reference, it generates command signals which are given to the driver circuitry to execute sparking events at appropriate crankshaft positions.

It should be noted that the system described in Figure 14 can be used in any one of the two commonly used configurations of ignition system hardware, the capacitive discharge ignition and the transistorized ignition. The capacitive discharge ignition uses energy stored in a capacitor to provide the sparking energy, while a transistorized ignition uses energy stored in an inductor to provide the sparking energy. According to the type of ignition system hardware chosen, the ignition driving circuitry and the timing command computation methods will need to be suitably chosen.

It should be noted that the system described in this invention can either constitute a stand-alone ignition system, such as one used in many carburetted IC engines, or can be part of an overall engine management system such as one used in IC engines equipped with an electronic fuel-injection system.

The system described in this invention can be used when a crankshaft position transducer is the only available sensor. In such condition, crankshaft position transducer can be used for computation of engine speed. Using engine speed, optimal ignition timing can be computed as shown in Figure 13. Using ignition timing so calculated, and using output of the crankshaft position transducer, appropriate timing commands can be generated for the ignition driving circuitry.

Although the invention has been described with reference to a specific embodiment, this description is not meant to be construed in a limiting sense. Various modifications of the disclosed embodiment, as well as alternate embodiments of the invention, will become apparent to persons skilled in the art upon reference to the description of the invention. It is therefore contemplated that such modifications can be made without departing from the spirit or scope of the invention as defined.

CLAIMS:

1. A system for controlling ignition timing of a spark-ignited internal combustion engine (84) comprising:
   a) plurality of sensors connected to said internal combustion engine;
   b) a sensor processing circuitry (141) processing output from said sensors in a microcontroller acceptable form;
   c) a microcontroller (142) processing output from said sensor processing circuitry (141) executing a method comprising the steps:
      i. computing a set of engine operating parameters (150; 152) indicative of engine operating conditions based on outputs of sensor processing circuitry (141);
      ii. determining a base ignition timing σ_{base} using said engine operating parameters (150; 152) and a pre-calibrated table (81);
      iii. determining engine operating conditions based on said engine operating parameters (150; 152);
      iv. deciding if slope-seeking controller (82) computations are to be performed for said engine operation conditions determined in step (iii);
      v. determining parameters to be used in said slope-seeking controller (82) based on engine operating parameters (150; 152);
      vi. performing slope-seeking controller computations (83) based on slope-seeking controller parameters determined in step (v) to compute an ignition timing σ_{SSC};
      vii. adding the base ignition timing σ_{base} and the ignition timing σ_{SSC} to compute the resultant optimal ignition timing σ;

viii. generating command signals for an ignition driving circuitry based on ignition timing calculated in step (viii) and on output of the position transducer, output of which can be related to crankshaft position;

d) an ignition driving circuitry (143) connected to said microcontroller (142) for generating a spark in the internal combustion engine (84).

2. A system as claimed in claim 1 wherein if slope-seeking controller computations are not to be performed in step (b)(iv) as claimed in claim 1, integrator used in said slope-seeking controller is reset and σ_{SSC} is set to zero.

3. A system as claimed in claims 1 or 2, wherein said ignition driving circuitry (143) uses energy stored in a capacitor to provide a spark.

4. A system as claimed in claims 1 or 2, wherein said ignition driving circuitry (143) uses energy stored in an inductor to provide a spark.

5. A system as claimed in claim 1, wherein said sensor processing circuitry includes a position transducer to indicate operating condition of said internal combustion engine (84).

6. A method for controlling the ignition timing of a spark-ignited internal combustion engine (84) comprising the steps of:

a) determining a base ignition timing σ_{base} using a set of engine operating parameters (150; 152) and a pre-calibrated table (81);

b) determining engine operating conditions based on engine operating parameters (150; 152);

c) deciding (142) if slope-seeking controller (82) computations are to be performed for the engine operation conditions determined in step (b);

d) determining parameters (83) to be used in a slope-seeking controller (82) based on engine operating parameters (150; 152);

e) performing slope-seeking controller computations (142) based on slope-seeking controller parameters (150; 152) determined in step (d) to compute an ignition timing σ_{SSC};

f) adding the base ignition timing σ_{base} and the ignition timing σ_{SSC} to compute the resultant optimal ignition timing σ.

7. A system as claimed in claim 6, wherein if slope-seeking controller computations are not to be performed in step (b)(iv) as claimed in claim 6, integrator used in said slope-seeking controller is reset and σ_{SSC} is set to zero.

8. A method as claimed in claim 6 or 7, wherein engine speed is the only engine operating parameter (150; 152) used for calculation of ignition timing.

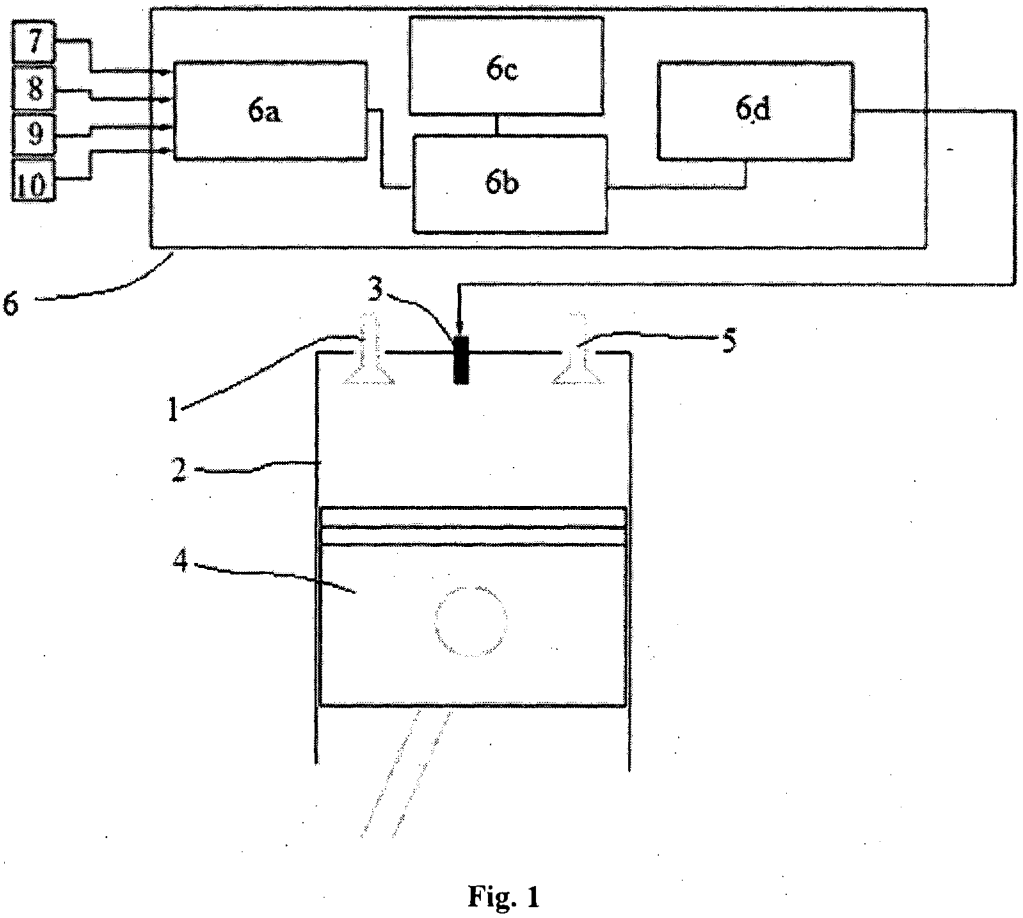

Fig. 1

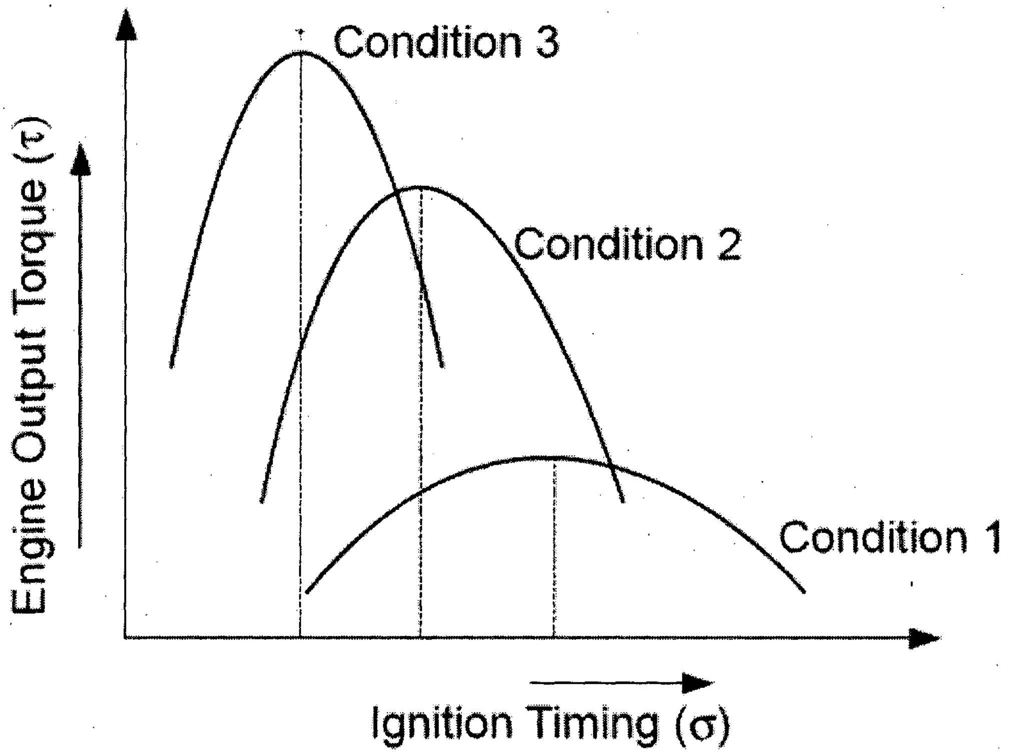
Condition 3
Condition 2
Condition 1
Engine Output Torque (τ)
Ignition Timing (σ)

Fig. 2

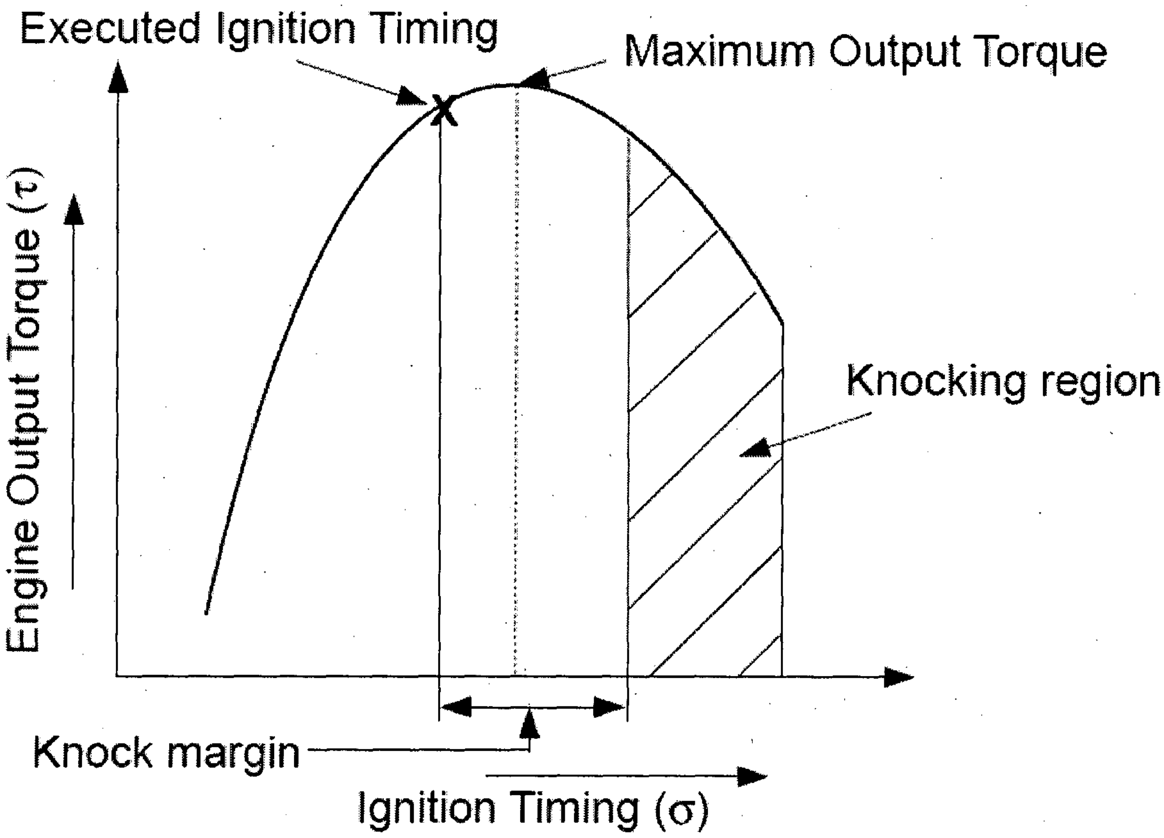
Executed Ignition Timing
Maximum Output Torque
Engine Output Torque (τ)
Knocking region
Knock margin
Ignition Timing (σ)

Fig. 3

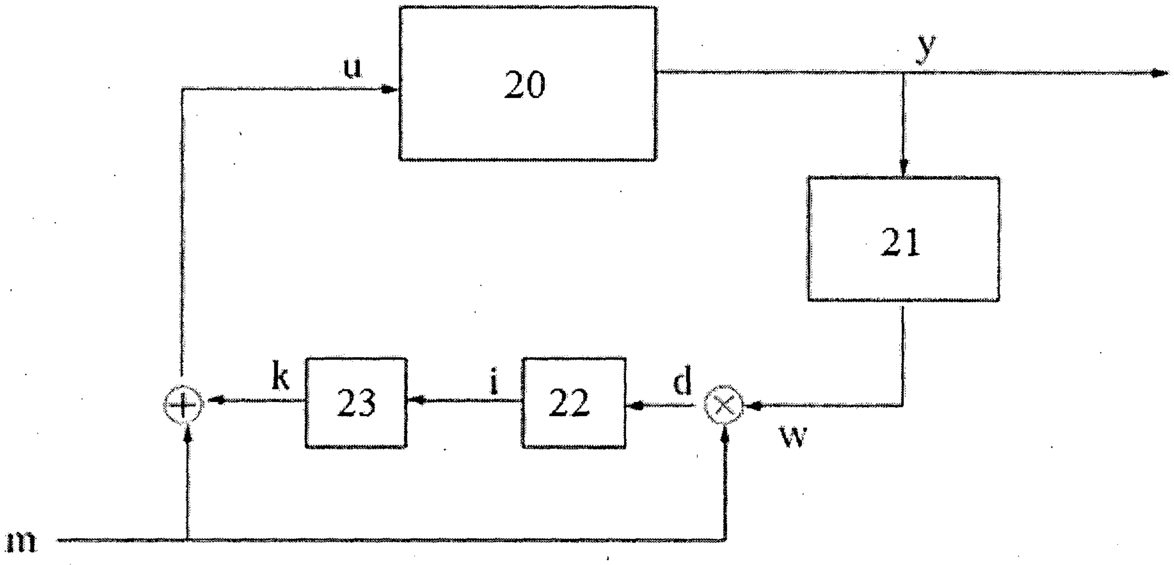

Fig. 4

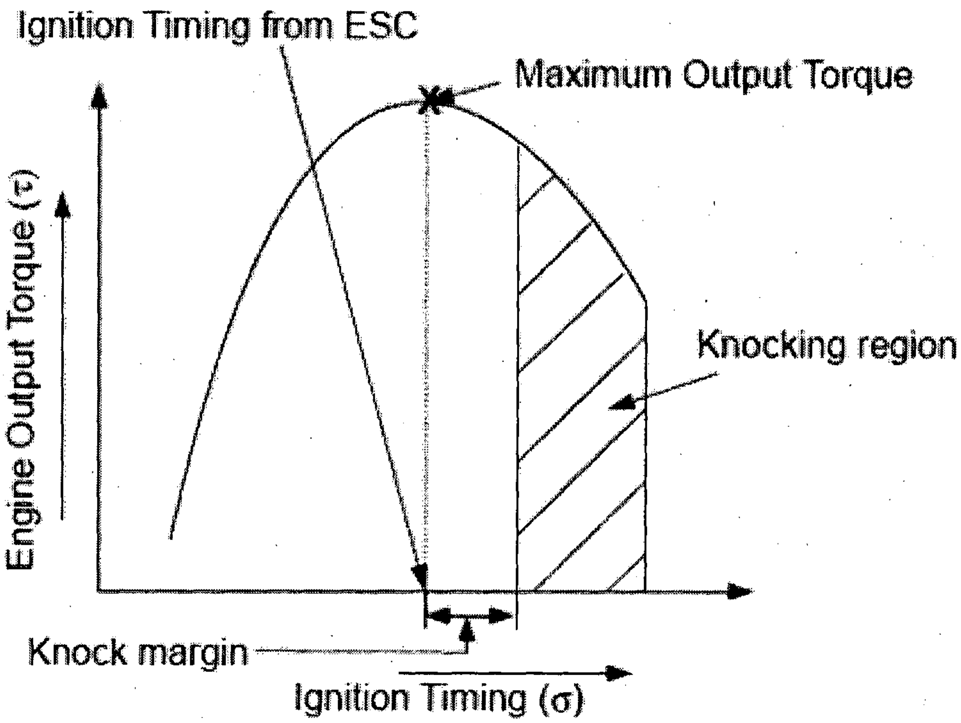
Ignition Timing from ESC
Maximum Output Torque
Engine Output Torque (τ)
Knocking region
Knock margin
Ignition Timing (σ)

Fig. 5

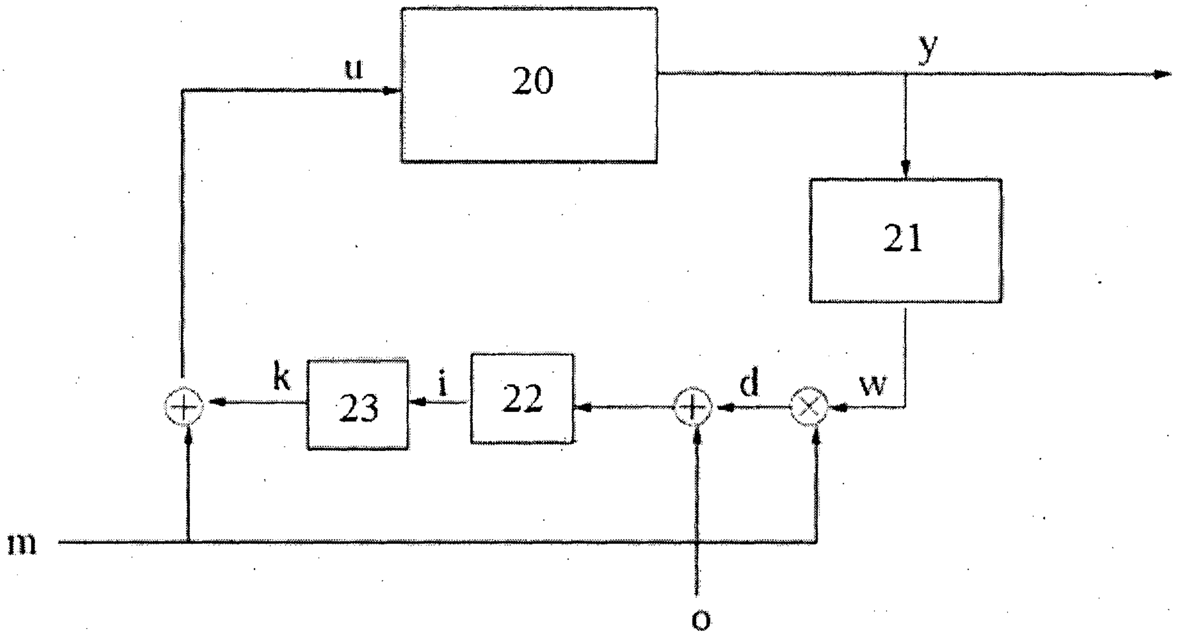

Fig. 6

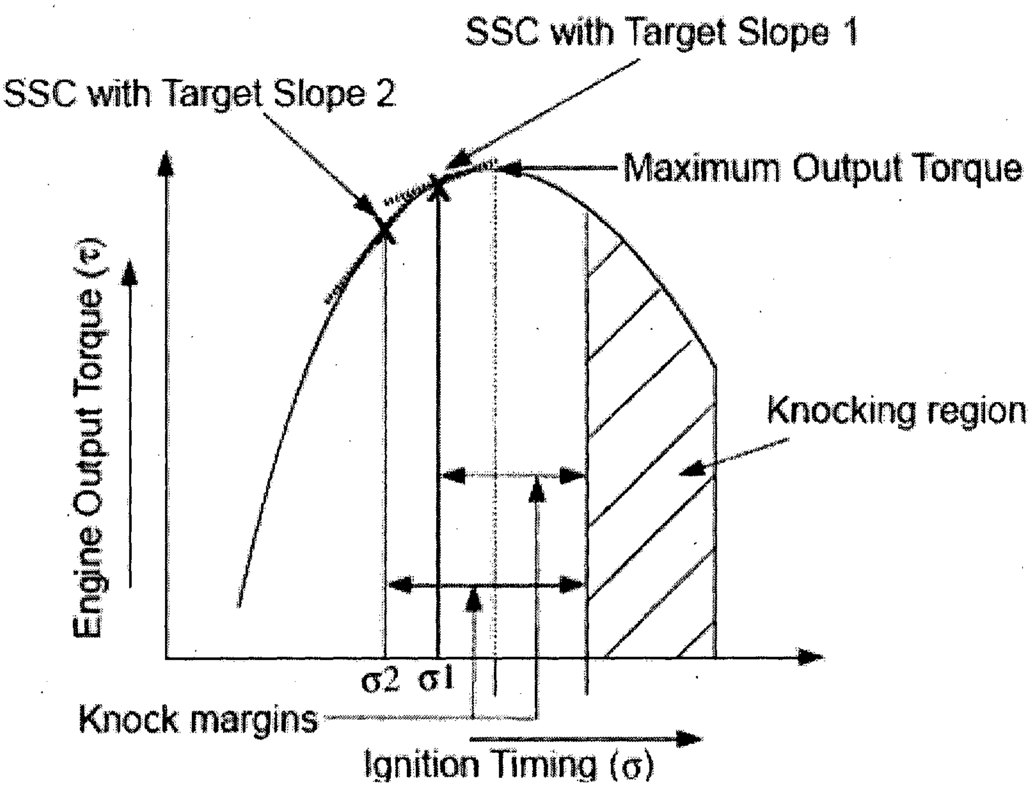
SSC with Target Slope 1
SSC with Target Slope 2
Maximum Output Torque
Engine Output Torque (τ)
Knocking region
σ2 σ1
Knock margins
Ignition Timing (σ)

Fig. 7

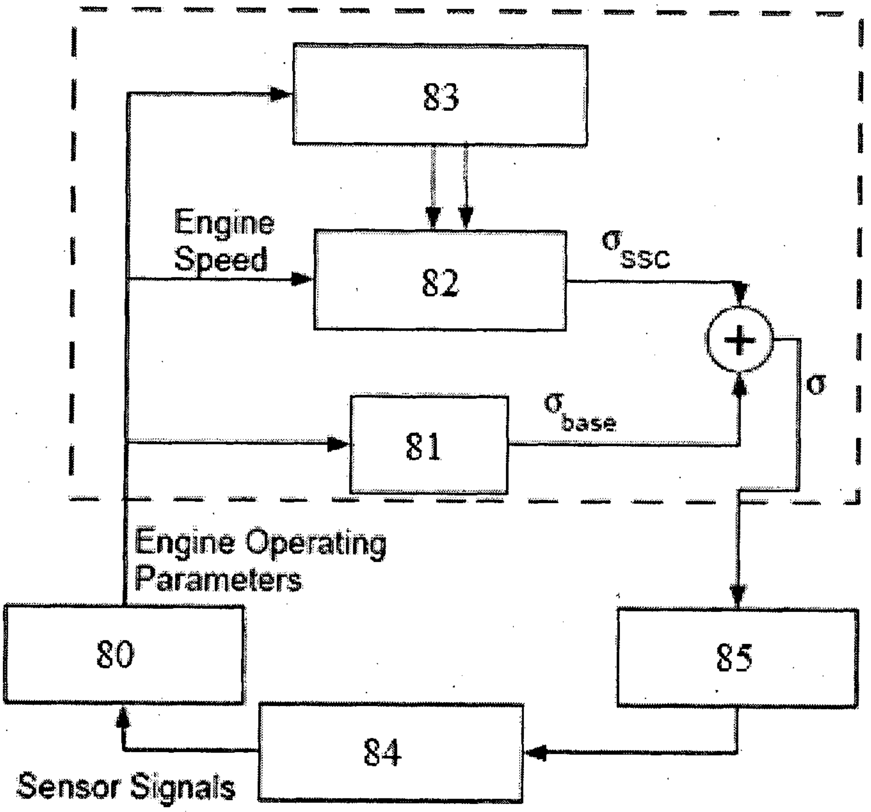
83
Engine Speed
82
σ_{ssc}
+
σ
81
σ_{base}
Engine Operating Parameters
80
85
84
Sensor Signals

Fig. 8

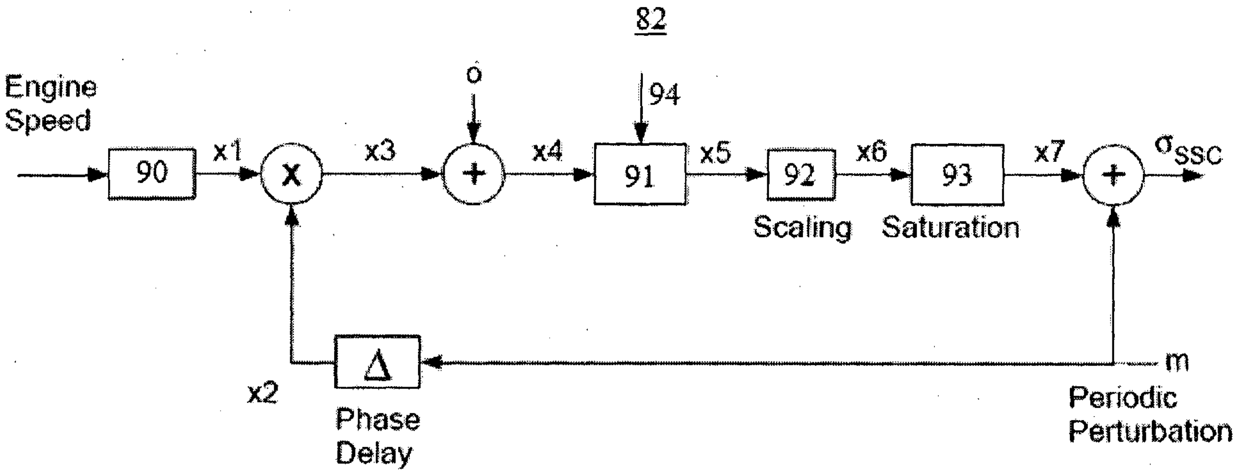
82
Engine Speed
90
x1
X
x3
ô
+
x4
94
91
x5
92
Scaling
x6
93
Saturation
x7
+
σ_{SSC}
x2
Δ
Phase Delay
m
Periodic Perturbation

Fig. 9

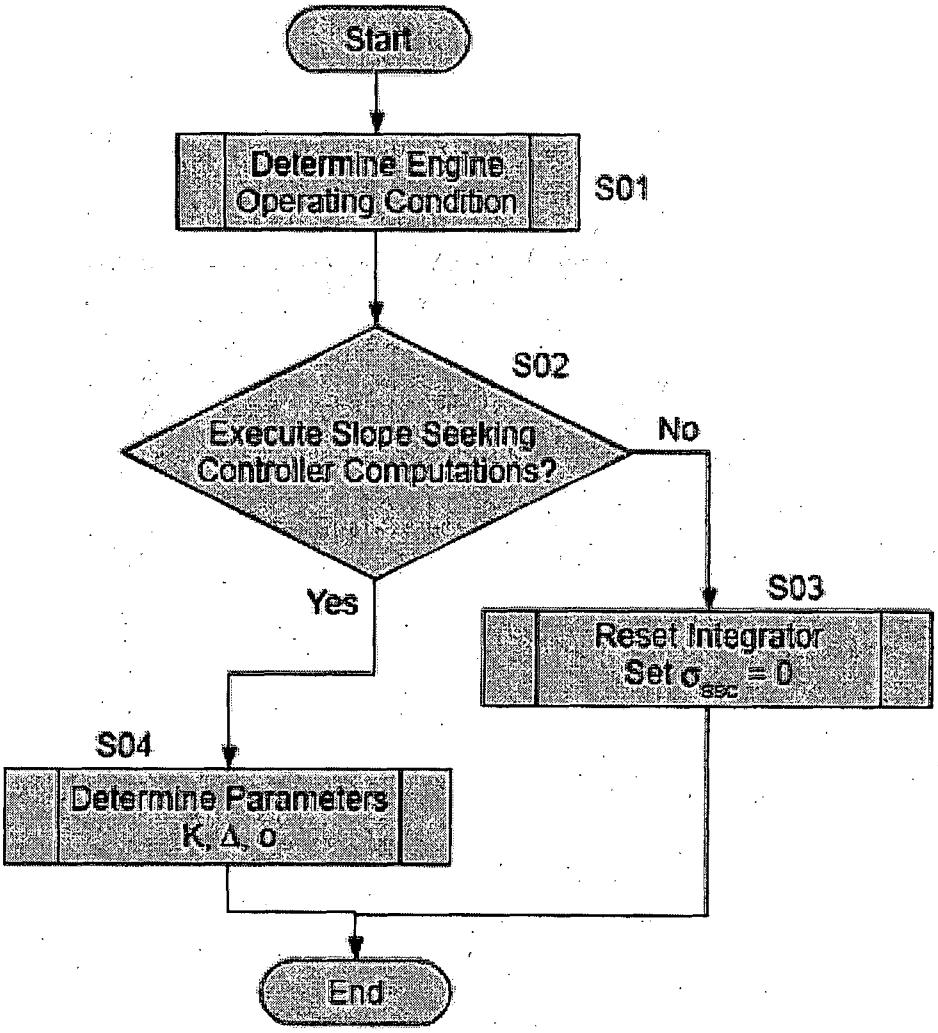
Start
Determine Engine Operating Condition
S01
S02
Execute Slope Seeking Controller Computations?
No
Yes
S03
Reset Integrator
Set $\sigma_{ssc} = 0$
S04
Determine Parameters
K, Δ, σ
End

Fig. 10

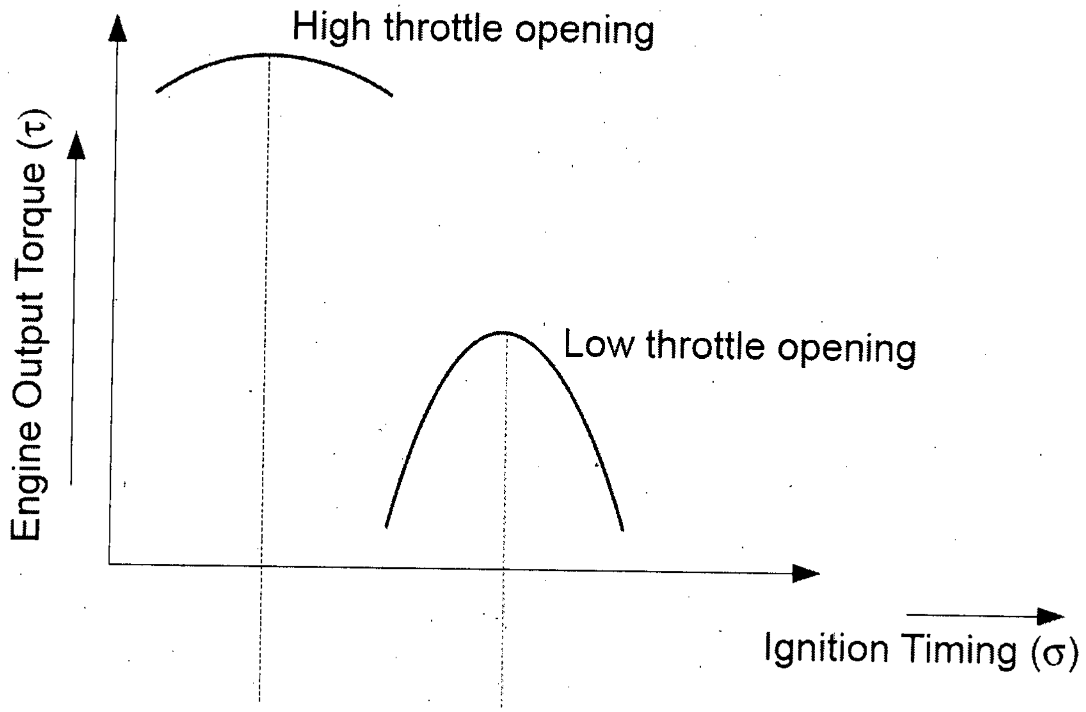
High throttle opening
Low throttle opening
Engine Output Torque (τ)
Ignition Timing (σ)

Fig. 11

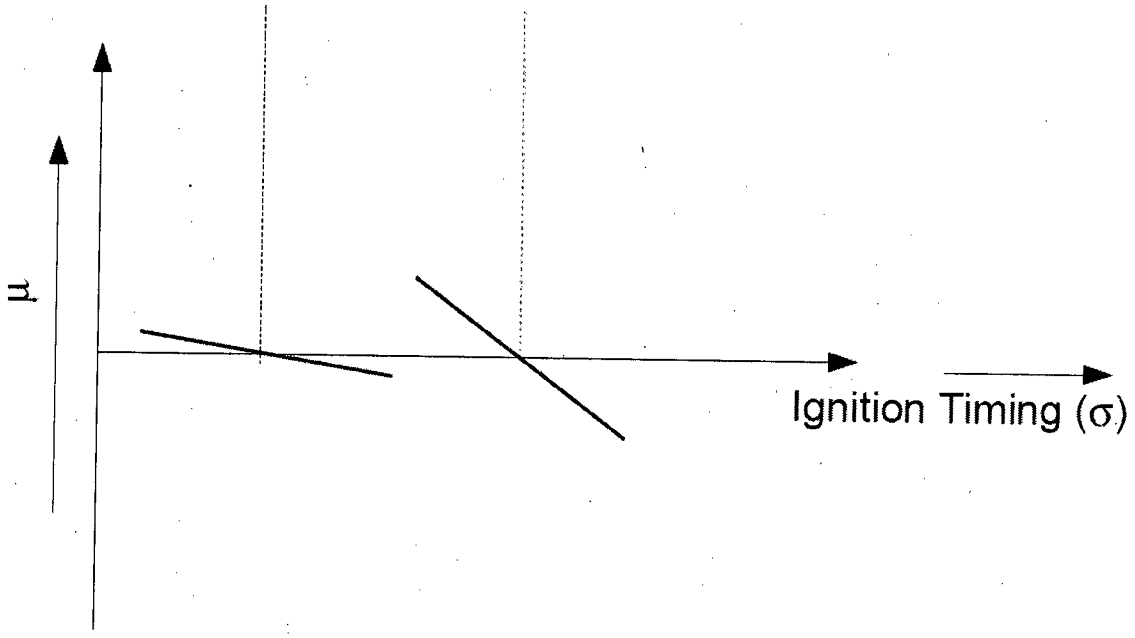
μ
Ignition Timing (σ)

Fig. 12

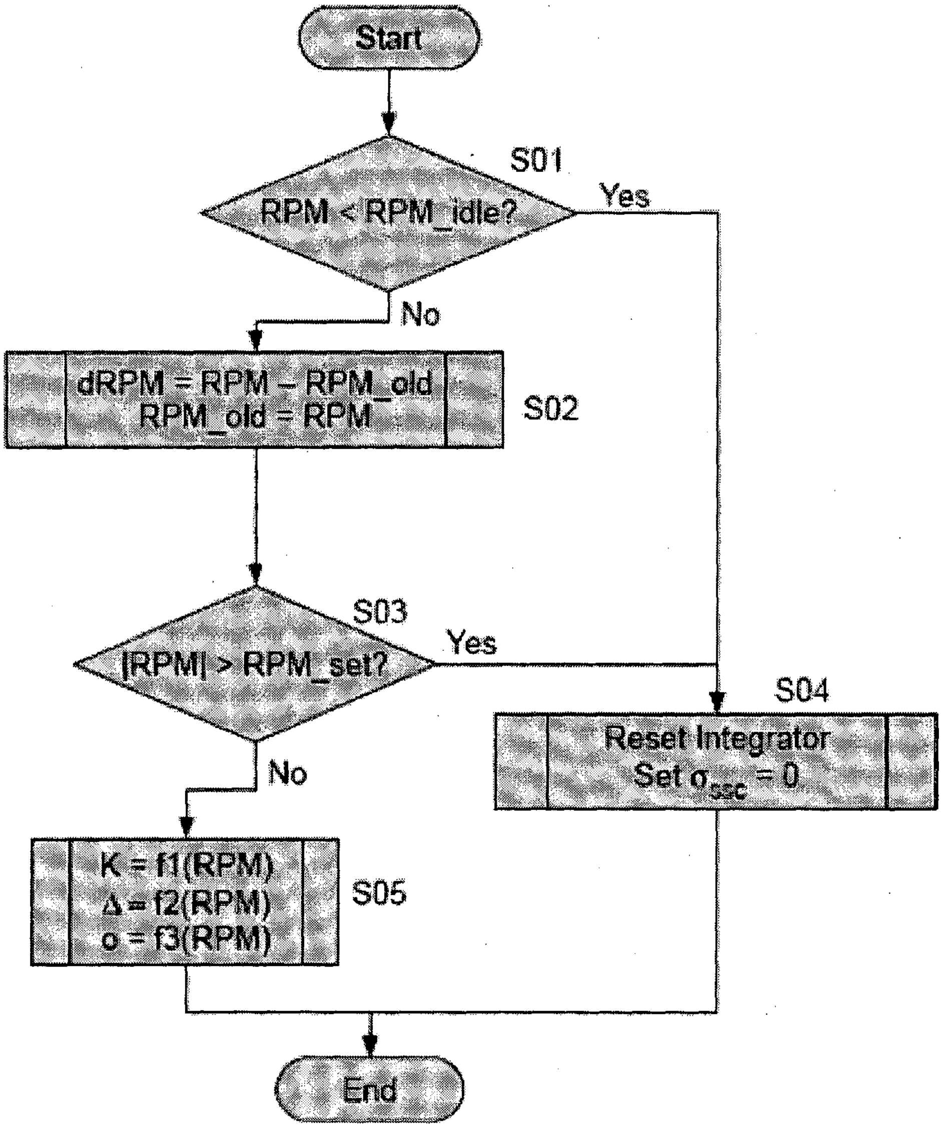
Start
S01
RPM < RPM_idle?
Yes
No
dRPM = RPM – RPM_old
RPM_old = RPM
S02
S03
|RPM| > RPM_set?
Yes
No
S04
Reset Integrator
Set σ_ssc = 0
K = f1(RPM)
Δ = f2(RPM)
o = f3(RPM)
S05
End

Fig. 13

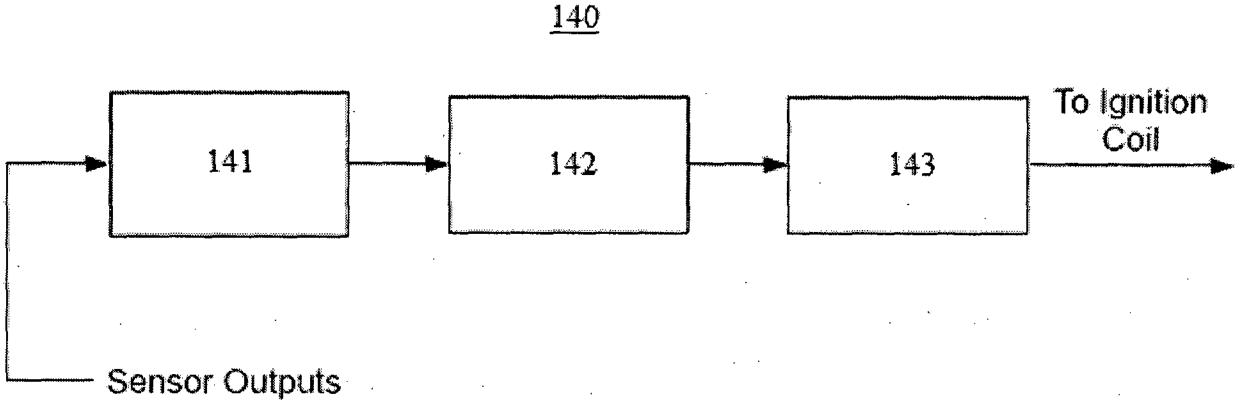

Fig. 14

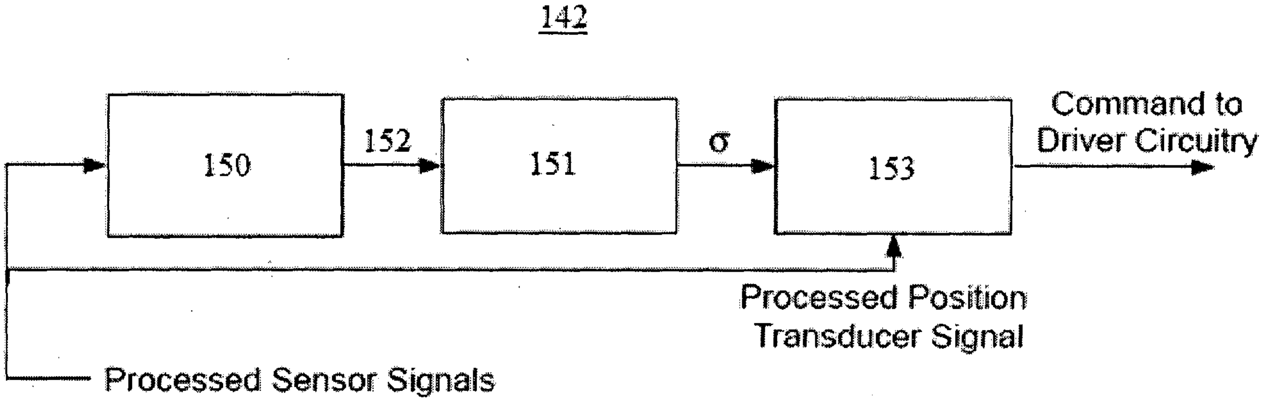
142
150
152
151
σ
153
Command to Driver Circuitry
Processed Position Transducer Signal
Processed Sensor Signals

Fig. 15