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[54] **AIR/FUEL RATIO CONTROL SYSTEM AND METHOD**

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[73] Assignee: **Ford Global Technologies, Inc.**, Dearborn, Mich.

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[51] **Int. Cl.**^{7} **F02D 41/18**

[52] **U.S. Cl.** **123/704**; 123/681; 701/104

[58] **Field of Search** 123/704, 681, 123/478, 480; 701/104; 73/118.2

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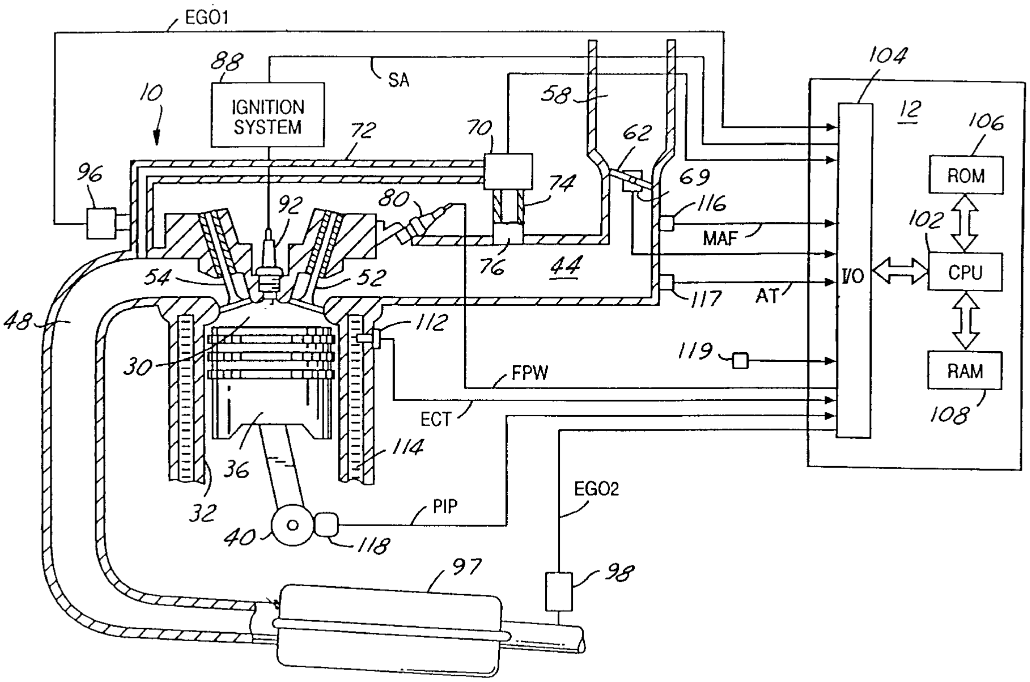
Primary Examiner—Erick Solis

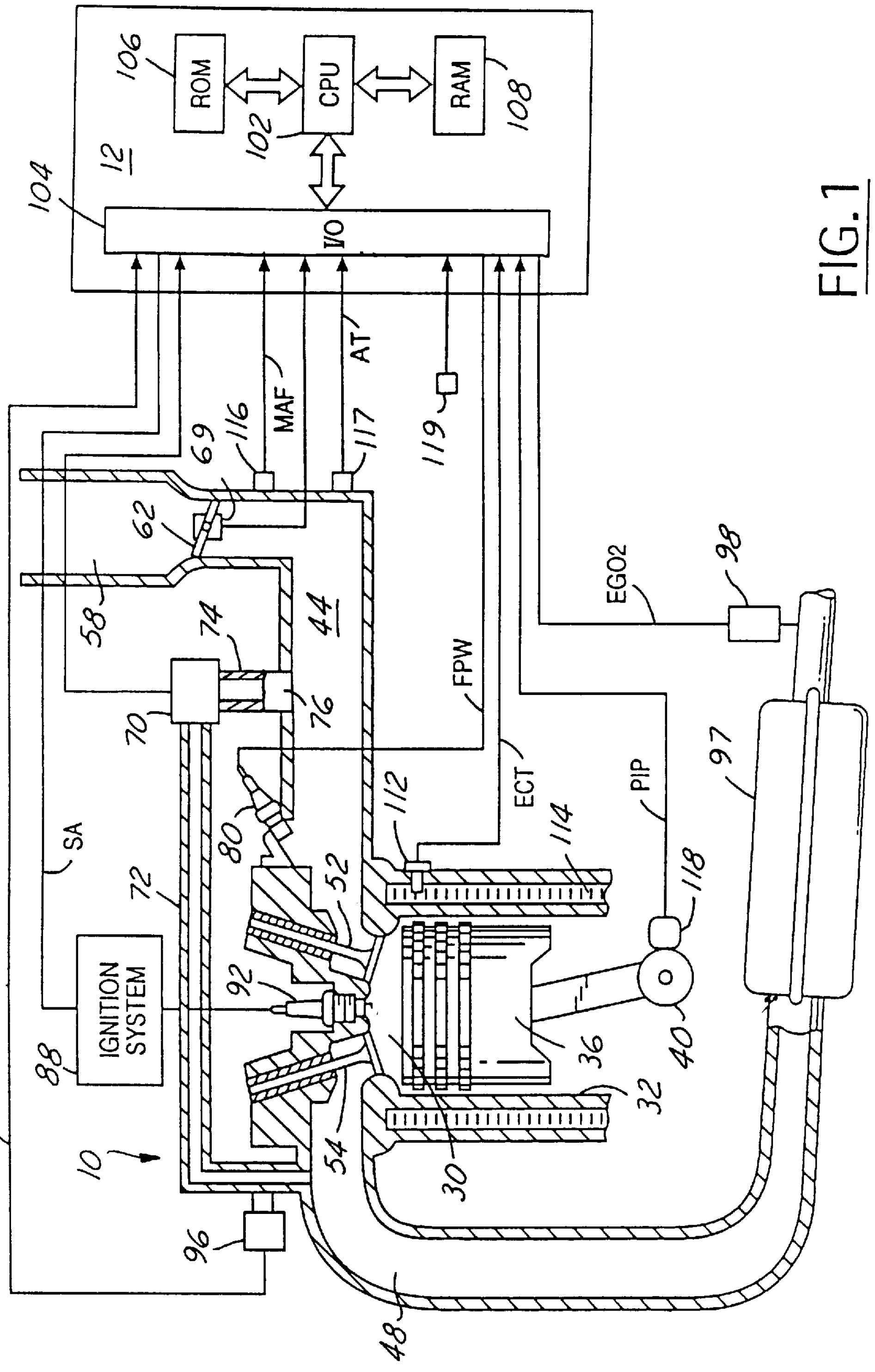
Attorney, Agent, or Firm—John D. Russell

[57] **ABSTRACT**

An air/fuel ratio control method for an internal combustion engine corrects airflow prediction errors. The method compares the current airflow to the value that was predicted several events in the past and creates an error signal. Based on this error signal, the current fueling is adjusted. These two mixtures, with equally offsetting lean and rich air/fuel ratios allow the catalytic converter to operate at peak efficiency despite prediction errors.

19 Claims, 4 Drawing Sheets

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ECT
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EGO1
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IGNITION SYSTEM
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98

FIG. 1

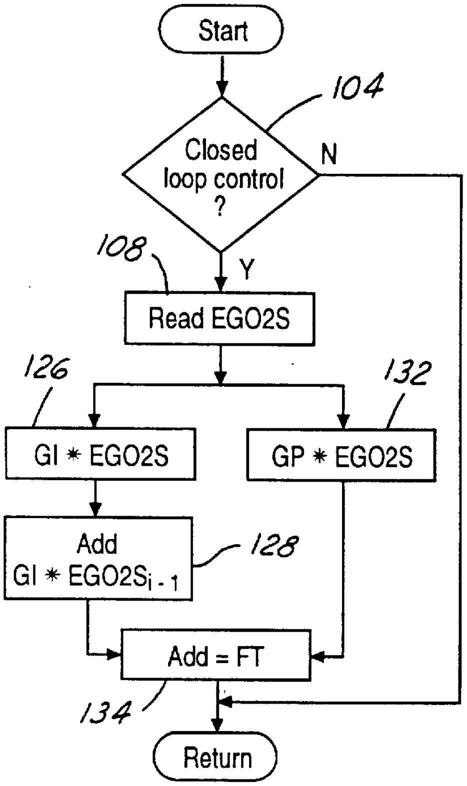
Start
104
Closed loop control ?
N
Y
108
Read EGO2S
126
132
GI ∗ EGO2S
GP ∗ EGO2S
Add GI ∗ EGO2S$_{i-1}$
128
Add = FT
134
Return

FIG. 2

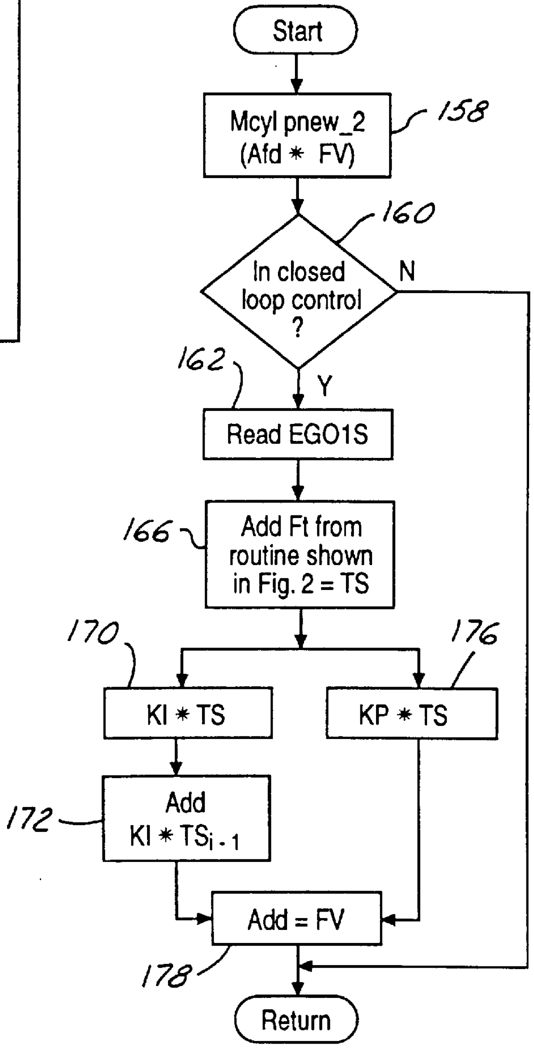
Start
Mcyl pnew_2 (Afd ∗ FV)
158
160
In closed loop control ?
N
Y
162
Read EGO1S
166
Add Ft from routine shown in Fig. 2 = TS
170
176
KI ∗ TS
KP ∗ TS
172
Add KI ∗ TS$_{i-1}$
Add = FV
178
Return

FIG. 3

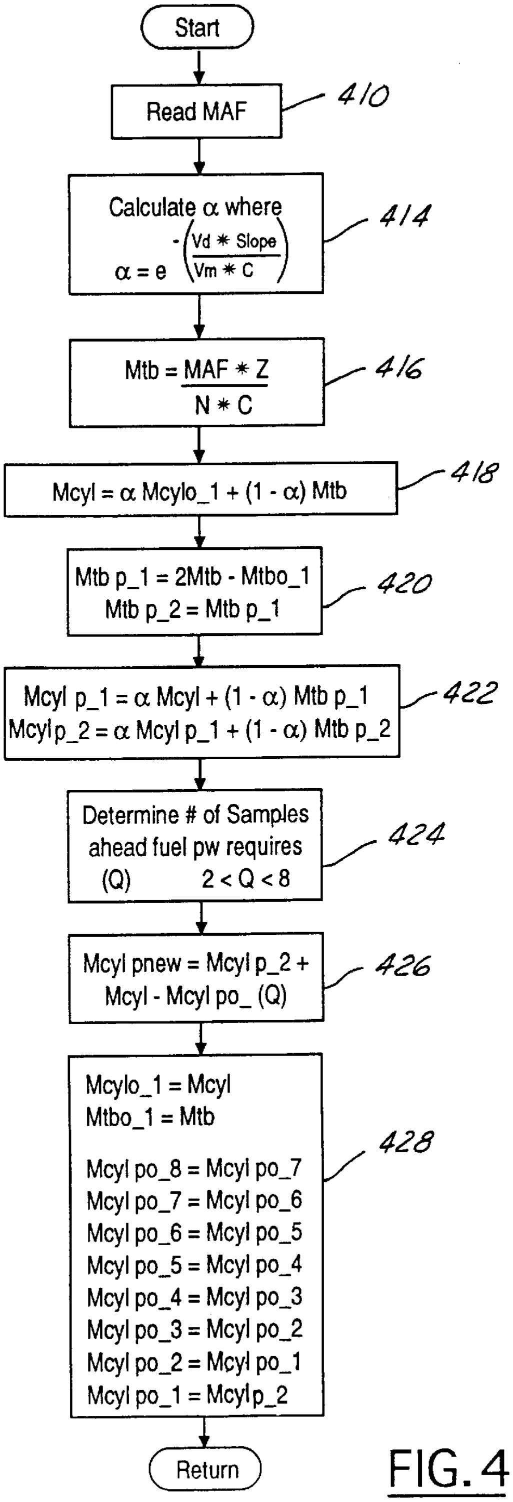
Start
Read MAF
410
Calculate α where
α = e^-(Vd * Slope / Vm * C)
414
Mtb = MAF * Z / N * C
416
Mcyl = α Mcylo_1 + (1 - α) Mtb
418
Mtb p_1 = 2Mtb - Mtbo_1
Mtb p_2 = Mtb p_1
420
Mcyl p_1 = α Mcyl + (1 - α) Mtb p_1
Mcyl p_2 = α Mcyl p_1 + (1 - α) Mtb p_2
422
Determine # of Samples ahead fuel pw requires (Q) 2 < Q < 8
424
Mcyl pnew = Mcyl p_2 + Mcyl - Mcyl po_ (Q)
426
Mcylo_1 = Mcyl
Mtbo_1 = Mtb
Mcyl po_8 = Mcyl po_7
Mcyl po_7 = Mcyl po_6
Mcyl po_6 = Mcyl po_5
Mcyl po_5 = Mcyl po_4
Mcyl po_4 = Mcyl po_3
Mcyl po_3 = Mcyl po_2
Mcyl po_2 = Mcyl po_1
Mcyl po_1 = Mcyl p_2
428
Return

FIG. 4

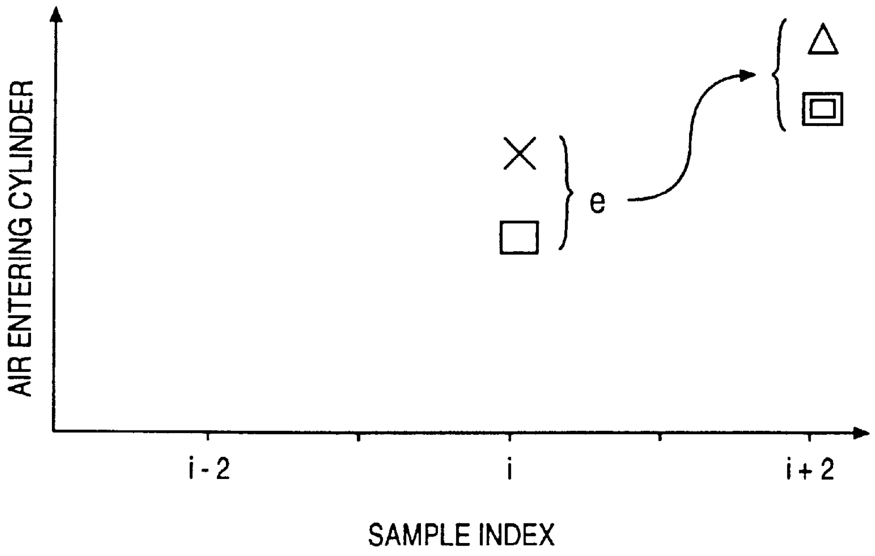

FIG. 5

AIR/FUEL RATIO CONTROL SYSTEM AND METHOD

FIELD OF THE INVENTION

The invention relates to air/fuel ratio control of an internal combustion engine where an air quantity entering a cylinder of the engine is predicted.

BACKGROUND OF THE INVENTION

Engine control systems inject fuel into the engine to maintain a desired air/fuel ratio necessary for controlling regulated emissions. In certain applications, the amount of fuel injected is based on an estimate of air entering the cylinder to maintain a desired air fuel ratio. The estimate of air entering the cylinder is based on a measurement of airflow entering the intake manifold of the engine. In addition, other parameters such as engine speed are utilized.

Because injecting fuel takes a finite amount of time and, in certain cases, fuel is injected before the air actually enters the cylinder, the actual amount of air that enters the cylinder is different from that which was estimated and used in the calculation of the fuel injection amount. For example, engine operating parameters, such as throttle position, can change between the time when the estimate was made and fuel injection amount calculated and the time when the fuel was actually injected. Thus, an error in the air fuel ratio results.

One method of improving air/fuel ratio control is to predict a future value of air entering the cylinder (or a future value of manifold pressure) and then use this prediction to calculate the fuel injection amount. The prediction is based on the current operating conditions and various models representing the physical processes of the internal combustion systems. Such a system is disclosed in U.S. Pat. No. 5,069,184.

The inventors herein have recognized a disadvantage with the above approach. For example, the approach attempts to predict the future value of air entering the cylinder. Thus, there will always be an error because perfect prediction is not possible. The prediction error will translate directly to an error in the air/fuel ratio, thereby affected the production of regulated emissions.

SUMMARY OF THE INVENTION

An object of the invention claimed herein is to provide an air/fuel ratio control system for an internal combustion engine insensitive to errors in predicting air entering the cylinder.

The above object is achieved, and problems of prior approaches overcome, by a method for controlling an air/fuel ratio in a cylinder of an internal combustion engine, said engine coupled to an emission control device. The method comprises, at a first sample index, estimating an air quantity inducted into the cylinder during a second sample index which follows said first sample index; at said second sample index calculating an actual air quantity inducted into the cylinder during said second sample index; and adjusting a fuel injection quantity based on said estimated air quantity and said actual air quantity to reduce an increase in emissions from the emission control device which would otherwise occur.

By calculating estimated and actual air entering the cylinder, and using this to correct fuel injection, it is possible to exploit the exhaust gas mixing in the exhaust manifold and the inherent storage in the catalytic converter. These processes, in combination with the present invention, allow past fueling errors due to prediction error to be corrected. Thus, the present invention will intentionally inject a lean mixture if a rich mixture was previously unintentionally injected. Then, using the exhaust mixing and catalyst storage properties, the lean and rich mixtures nullify each other in the catalytic converter and regulated emissions are minimized.

An advantage of the present invention is the ability to operate the catalytic converter at peak efficiency.

Another advantage of the present invention is the ability to reduce regulated emissions.

Other objects, features and advantages of the present invention will be readily appreciated by the reader of this specification.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects and advantages described herein will be more fully understood by reading an example of an embodiment in which the invention is used to advantage, referred to herein as the Description of Preferred Embodiment, with reference to the drawings, wherein:

FIG. **1** is a block diagram of an embodiment wherein the invention is used to advantage; and

FIGS. **2**–**4** are high level flow charts of various operations performed by a portion of the embodiment shown in FIG. **1**; and

FIG. **5** is a graph illustrating application of the present invention.

DESCRIPTION OF PREFERRED EMBODIMENT

Internal combustion engine **10**, comprising a plurality of cylinders, one cylinder of which is shown in FIG. **1**, is controlled by electronic engine controller **12**. Engine **10** includes combustion chamber **30** and cylinder walls **32** with piston **36** positioned therein and connected to crankshaft **40**. Combustion chamber **30** is known communicating with intake manifold **44** and exhaust manifold **48** via respective intake valve **52** and exhaust valve **54**. Intake manifold **44** is shown communicating with throttle body **58** via throttle plate **62**. Throttle position sensor **69** measures position of throttle plate **62**. Exhaust manifold **48** is shown coupled to exhaust gas recirculation valve **76** via exhaust gas recirculation tube **72** having exhaust gas flow sensor **70** therein for measuring an exhaust gas flow quantity. Exhaust gas recirculation valve **76** is also coupled to intake manifold **44** via orifice tube **74**. Intake manifold **44** is also shown having fuel injector **80** coupled thereto for delivering liquid fuel in proportion to the pulse width of signal FPW from controller **12**. Fuel is delivered to fuel injector **80** by a conventional fuel system (not shown) including a fuel tank, fuel pump, and fuel rail (not shown). Alternatively, the engine may be configured such that the fuel is injected directly into the cylinder of the engine, which is known to those skilled in the art as a direct injection engine.

Conventional distributorless ignition system **88** provides ignition spark to combustion chamber **30** via spark plug **92** in response to controller **12**. Two-state exhaust gas oxygen sensor **96** is shown coupled to exhaust manifold **48** upstream of catalytic converter **97**. Two-state exhaust gas oxygen sensor **98** is shown coupled to exhaust manifold **48** downstream of catalytic converter **97**. Sensor **96** provides signal EGO1 to controller **12** which converts signal EGO1 into two-state signal EGO1S. A high voltage state of signal EGO1S indicates exhaust gases are rich of a reference air/fuel ratio and a low voltage state of converted signal EGO1 indicates exhaust gases are lean of the reference air/fuel ratio. Sensor **98** provides signal EGO2 to controller **12** which converts signal EGO2 into two-state signal EGO2S. A high voltage state of signal EGO2S indicates exhaust gases are rich of a reference air/fuel ratio and a low voltage state of converted signal EGO2S indicates exhaust gases are lean of the reference air/fuel ratio.

Controller **12** is shown in FIG. **1** as a conventional microcomputer including: microprocessor unit **102**, input/output ports **104**, read-only memory **106**, random access memory **108**, and a conventional data bus. Controller **12** is shown receiving various signals from sensors coupled to engine **10**, in addition to those signals previously discussed, including: engine coolant temperature (ECT) from temperature sensor **112** coupled to cooling sleeve **114**; a measurement of mass air flow measurement (MAF) from mass flow sensor **116** coupled to intake manifold **44**; a measurement (MT) of manifold temperature from temperature sensor **117**; a profile ignition pickup signal (PIP) from Hall effect sensor **118** coupled to crankshaft **40**, and an engine speed signal (RPM) from engine speed sensor **119**. In a preferred aspect of the present invention, engine speed sensor **119** produces a predetermined number of equally spaced pulses every revolution of the crankshaft.

Referring now to FIG. **2**, a flowchart of a routine performed by controller **12** to generate fuel trim signal FT is now described. A determination is first made whether closed-loop air/fuel control is to be commenced (step **122)** by monitoring engine operation conditions such as temperature. When closed-loop control commences, signal EGO2S is read from sensor **98** (step **124**) and subsequently processed in a proportional plus integral controller as described below.

Referring first to step **126**, signal EGO2S is multiplied by gain constant GI and the resulting product added to products previously accumulated ($GI*EGO2S_{i-1}$) in step **128**. Stated another way, signal EGO2S is integrated each sample period (i) in steps determined by gain constant GI. During step **132**, signal EGO2S is also multiplied by proportional gain GP. The integral value from step **128** is added to the proportional value from step **132** during addition step **134** to generate fuel trim signal FT.

The routine executed by controller **12** to generate the desired quantity of liquid fuel delivered to engine **10** and trimming this desired fuel quantity by a feedback variable related both to sensor **98** and fuel trim signal FT is now described with reference to FIG. **3**. During step **158**, an open-loop fuel quantity is first determined by dividing the estimated air entering the cylinder for a predicted cylinder (Mcylpnew as described later herein with particular reference to FIG. **4**), by desired air/fuel ratio Afd, which is typically the stoichiometric value for gasoline combustion. However, setting AFd to a rich value will result in operating the engine in a rich state. Similarly, setting AFd to a lean value will result in operating the engine in a lean state. This open-loop fuel quantity is then adjusted, in this example divided, by feedback variable FV.

After determination that closed-loop control is desired (step **160**) by monitoring engine operating conditions such as temperature (ECT), signal EGO1S is read during step **162**. During step **166**, fuel trim signal FT is transferred from the routine previously described with reference to FIG. **2** and added to signal EGO1S to generate trim signal TS.

During steps **170–178**, a proportional plus integral feedback routine is executed with trimmed signal TS as the input. Trim signal TS is first multiplied by integral gain value KI (step **170**), and the resulting product added to the previously accumulated products (step **172**). That is, trim signal TS is integrated in steps determined by gain constant KI each sample period (i) during step **172**. A product of proportional gain KP times trimmed signal TS (step **176**) is then added to the integration of KI*TS during step **178** to generate feedback variable FV.

According to the present invention, referring now to FIG. **4**, a flowchart of a routine performed by controller **12** to estimate the quantity of air entering the cylinder is described. The routine is executed at constant intervals of engine rotation to simplify calculations. For example, airflow measurement is simplified because of airflow pulsations that occur synchronously with the sampling interval. In step **410**, the value of mass air flow sensor (MAF) **116** is read. As is known to those skilled in the art, signal MAF is also used to represent an engine load during stociometric conditions. Then, in step **414**, the filter parameter (a) is determined by the following function:

$$\alpha=e^{-(Vd*slope)/(Vm*C)}$$

where e is the exponential function, slope is the single calibratable parameter representing the slope of the graph between manifold pressure and cylinder air charge, and the following are all constant: Vd is the engine displacement volume, Vm is the manifold volume, and C is the number of cylinders.

A simplified function that approximates the expression shown above may also be used as is obvious to one of ordinary skill in the art and suggested by this disclosure. Also, if the routine is not executed at constant engine rotational intervals, the filter parameter would be calculated by the following function, where T is the sample time:

$$\alpha=e^{-(Vd*slope*T)/(N*Vm*C)}$$

Next, in step **416**, the current air entering the manifold, mtb is calculated by multiplying MAF by 2 then dividing by the engine speed (N) and the number of cylinders (C). Then, in step **418**, the current estimated value of the air entering the cylinder (Mcyl) is calculated using the filter parameter (α), the previous value of the air entering the cylinder one event in the past (Mcylo_**1**) and the current air entering the manifold (mtb), where event refers to combustion event. Next, in step **420**, a prediction is made of the airflow entering the manifold one step in the future (mtbp_**1**) based on the current airflow entering the manifold (mtb) and the previous value of airflow entering the manifold one event in the past (mtbo_**1**). A prediction is also made of the airflow entering the manifold two events in the future (mtbp_**2**) as being equal to mtbo_**1**. This is just one method for predicting airflow into the manifold in the future. Any method known to those skilled in the art and suggested by this disclosure could be used to perform this prediction. Any prediction method is suitable to be used to advantage according to the present invention.

Referring now to step **422**, the predicted airflows entering the manifold (mtbp_**1**, mtbp_**0**) are used with the current airflow entering the cylinder (mcyl) to predict the air entering the cylinder at one and two events in the future. This is just one method for predicting airflow into the cylinder in the future. Again, any method known to those skilled in the art and suggested by this disclosure could be used to perform this prediction. Any prediction method is suitable to be used to advantage according to the present invention.

Referring now to step **424**, a determination is made as to the number of events in the future (Q) for which the fuel pulse width (fpw) is calculated, where events again refers to combustion events. This is a function of engine speed and reflects the amount time an injector must be opened to allow the necessary fuel quantity to be injected. As engine speed increases, the fuel injection time must be scheduled earlier. This function can be found experimentally or analytically based on the fuel injector characteristics and required fuel injection quantity. A typical value for a V–8 engine is two events. Thus, the fuel amount being calculated by the engine controller will be injected into the cylinder that will fire two combustion events in the future. Thus, the prediction of two events directly matches this value. However, in some instances, the value of Q can be as large as 8.

Referring now to step **426**, the prediction of airflow entering the cylinder two events in the future (mcylp__**2**) is modified based on an error signal (e). The error signal represents the fuel error caused by previous predictions of the airflow entering the cylinder that did not match the actual airflow entering the cylinder. This error is known because the previous predictions can be compared with the airflow entering the cylinder based on non-predicted (current) measurements. The modified airflow (mcylpnew) is determined based on the predicted value of airlflow entering the cylinder (mcylp__**2**), the current airflow entering the cylinder (mcyl) and the predicted airflow entering the cylinder to which the current airflow entering the cylinder (mcyl) corresponds. For example, if Q=2, then:

$$mcylpnew=mcylp\_\_2+mcyl-mcylpo\_\_2$$

where, mcylpo__**2** represents the predicted airflow (that was predicted **2** events in the past) that should have matched the current value of mcyl. If, for example, Q=3, then:

$$mcylpnew=mcylp\_\_2+mcyl-mcylpo\_\_3$$

where, mcylpo__**3** represents the predicted airflow (that was predicted 3 events in the past) that should have matched the current value of mcyl.

Referring now to step **428**, past values are saved in memory for future use as described above herein.

Referring now to FIG. **5**, a graph illustrating application of the present invention is shown. The graph shows how the present invention operates at generic sample index when the value of Q=2. At generic sample index (i), the square represents the predicted air entering the manifold that was predicted at generic sample index (i–2). This value was used to calculate the fuel that was injected into the cylinder firing at generic sample index (i). However, at generic sample index (i), the current measurements processed as described above herein with particular reference to FIG. **4**, give an actual value of air entering the cylinder represented by the cross. This means that an error (e) was made in the fueling operation and since this cylinder is currently firing, it is too late to correct this error in the firing cylinder.

However, according to the present invention, this error is used to correct the next possible cylinder firing, assuming that the gasses for both cylinders will mix in an exhaust volume and enter a common catalytic converter. As shown in FIG. **5** by the double square, at generic sample index (i), a prediction is made as to the air entering the cylinder that will fire at generic sample index (i+2) as described above herein with particular reference to FIG. **4**. Then, this prediction is augmented with the error (e) to form a new value used for fueling as shown by the triangle. In this way, past prediction errors can be corrected for and improvements in tailpipe emissions can be realized.

Although several examples of embodiments which practice the invention have been described herein, there are numerous other examples which could also be described. For example, the invention may be used to advantage with carbureted engines, proportional exhaust gas oxygen sensors, and engines having an in-line configuration rather than a V-configuration. Further, if there are multiple cylinder banks in which the exhaust gases from the respective banks do not mix before a catalyst, then fueling error must be corrected on a per bank basis.

Also, when operating on a direct injection type internal combustion engine, the number of events into the future for which the prediction must be made is reduced because, in stratified operation, some fuel is directed during the compression stroke of the engine, while some is injected during the intake stroke. The number of events is reduced because there is less of a delay between airflow calculation and intake valve closing.

The invention is therefore to be defined only in accordance with the following claims.

We claim:

1. A method for controlling an internal combustion engine coupled to an emission control device, the method comprising:

at a first sample index, predicting a value of an engine operating parameter occurring during a second sample index;

injecting a first fuel amount into the engine based on said predicted value;

determining whether said first injected fuel amount resulted in an inadvertent air/fuel ratio error; and

offsetting said air/fuel ratio error by injecting a second fuel amount at an index after said first index based on an actual value of said engine operating parameter.

2. The method recited in clam **1**, wherein said engine operating parameter is an air quantity inducted into the engine.

3. The method recited in clam **1**, wherein said sample indices represent cylinder firing events.

4. The method recited in clam **3**, wherein said second sample index occurs at predetermined number of cylinder firing events after said first sample index.

5. The method recited in clam **4**, wherein said predetermined number of cylinder firing events is adjusted based on engine operating conditions.

6. The method recited in claim **5**, wherein said engine operating conditions comprise an engine speed and load.

7. The method recited in clam **4**, wherein said predetermined number of cylinder events is decreased when the engine is operating in the stratified mode.

8. The method recited in clam **1**, wherein said first injected fuel amount forms a first air/fuel mixture, and said second injected fuel amount forms a second air/fuel mixture, and said first air/fuel mixture and said second air/fuel mixture meet to form a third air/fuel mixture which enters the emission control device.

9. A method for controlling an internal combustion engine having a first group of at least one cylinder coupled to a first emission control device and a second group of at least one cylinder coupled to a second emission control device, the method comprising:

at a first sample index, predicting an air induction amount entering one of said first and second cylinder groups during a second sample index occurring after said first sample index;

injecting a first fuel amount into said one of said first and second cylinder groups based on said predicted value;

determining whether said first injected fuel amount resulted in an inadvertent air/fuel ratio error in said one of said first and second cylinder groups; and

offsetting said air/fuel ratio error by injecting a second fuel amount into said one of said first and second cylinder groups at an index after said first index based on an actual air induction amount entering said one of said first and second cylinder groups.

10. The method recited in claim **9**, wherein said sample indices represent cylinder firing events.

11. The method recited in claim **10**, wherein said second sample index occurs a predetermined number of cylinder events after said first sample index.

12. The method recited in claim **11**, wherein said predetermined number of cylinder firing events is adjusted based on engine operating conditions.

13. The method recited in claim **12**, wherein said engine operating conditions comprise an engine speed and load.

14. The method recited in claim **9**, wherein said first injected fuel amount is injected into a first cylinder of said one of said first and second cylinder groups, and said second injected fuel amount is injected into a second cylinder of said one of said first and second cylinder groups.

15. The method recited in claim **11**, wherein said predetermined number of cylinder firing events is decreased when operating the engine in a stratified mode.

16. The method recited in claim **9**, wherein said emission control device is a catalytic converter.

17. The method recited in claim **9**, wherein said step of injecting said first fuel amount into said one of said first and second cylinder groups based on said predicted value further comprising adjusting said first injected fuel amount based on a signal from an exhaust sensor coupled to the engine.

18. A method for controlling an internal combustion engine coupled to an emission control device, the method comprising:

at a first sample index, predicting a value of an engine operating parameter occurring during a second sample index;

injecting fuel into the engine based on said predicted value;

determining whether said injected fuel resulted in an inadvertent lean air/fuel ratio, or an inadvertent rich air/fuel ratio; and

offsetting said inadvertent lean or rich air/fuel ratio by intentionally injecting a rich air/fuel mixture at an index after said first index if said inadvertent lean air/fuel ratio occurred, or intentionally injecting a lean air/fuel mixture at said index after said first index if said inadvertent rich air/fuel ratio occurred.

19. The method recited in claim **18**, wherein said engine operating parameter is an air induction amount.

* * * * *