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SYSTEMS AND METHODS FOR CATALYST SENSOR DIAGNOSTICS

Abstract

An apparatus includes a processing circuit structured to: receive a first signal indicative of an upstream air-fuel equivalence ratio from a first sensor positioned upstream of an intake of a catalyst; receive a second signal indicative of a downstream air-fuel equivalence ratio from a second sensor positioned downstream of the intake of the catalyst; provide a control signal to an engine to produce a desired first signal; predict an expected second signal based on the desired first signal; compare the first signal to the desired first signal; determine a second signal differential between the second signal and the expected second signal when the first signal is equal to the desired first signal; and, provide a fault signal in response to the second signal differential exceeding a threshold differential. A notification circuit is structured to provide a notification indicating that the second sensor is faulty.

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Background/Summary

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS [0001] This application is a continuation patent application of U.S. patent application Ser. No. 17/675,985, filed Feb. 18, 2022, which is a divisional application of U.S. patent application Ser. No. 16/466,923, filed Jun. 5, 2019, which is a national stage application of P.C.T. Application No. PCT/US2017/064848, filed Dec. 6, 2017, which claims the benefit of and priority to U.S. Provisional Patent Application No. 62/432,290, filed Dec. 9, 2016. All of these applications are incorporated herein by reference in their entireties and for all purposes.

TECHNICAL FIELD
[0002] The present disclosure relates to exhaust aftertreatment systems. More particularly, the present disclosure relates to operating an exhaust aftertreatment diagnostic system.
BACKGROUND
[0003] Emission regulations for internal combustion engines have become more stringent over recent years. Environmental concerns have motivated the implementation of stricter emission requirements for internal combustion engines throughout much of the world. Governmental agencies, such as the Environmental Protection Agency (EPA) in the United States, carefully monitor the emissions quality of engines and set acceptable emission standards, to which all engines must comply by law. For example, the California Air Resources Board (CARB) requires engine systems to diagnose any sensors used in emissions control systems for errors that may affect emission levels.
[0004] Three-way catalysts are a key component of emissions control systems in Stoichiometric Spark-Ignited engines, such as those fueled by gasoline, ethanol, and natural gas. CARB requires engine systems to monitor the three-way catalyst(s) for any malfunctions that might lead to system emissions exceeding a pre-defined threshold.
SUMMARY
[0005] One embodiment relates to an apparatus that includes a processing circuit structured to receive a first signal indicative of an upstream air-fuel equivalence ratio from a first sensor positioned upstream of an intake of a catalyst, receive a second signal indicative of a downstream air-fuel equivalence ratio from a second sensor positioned downstream of the intake of the catalyst, determine an actual oxygen storage capacity of the catalyst based at least in part on the received first signal and the received second signal, compare the actual oxygen storage capacity to a maximum storage capacity, and provide a fault signal in response to the actual oxygen storage capacity exceeding the maximum storage capacity. The apparatus also includes a notification circuit structured to provide a notification indicating that the second sensor is faulty in response to receiving the fault signal.
[0006] Another embodiment relates to an apparatus that includes a processing circuit structured to receive a first signal indicative of an upstream air-fuel equivalence ratio from a first sensor positioned upstream of an intake of a catalyst, receive a second signal indicative of a downstream air-fuel equivalence ratio from a second sensor positioned downstream of the intake of the catalyst,

determine a statistical metric of the upstream air-fuel equivalence ratio based on the first signal, determine a statistical metric of the downstream air-fuel equivalence ratio based on the second signal, compare the statistical metrics to determine a differential, and provide a fault signal in response to the statistical metric differential exceeding a predetermined threshold. The apparatus also includes a notification circuit structured to provide a notification indicating that the second sensor is faulty in response to receiving the fault signal.

[0007] Another embodiment relates to an apparatus that includes a processing circuit structured to receive a first signal indicative of an upstream air-fuel equivalence ratio from a first sensor positioned upstream of an intake of a catalyst. The first signal defines a duty cycle. The processing circuit is further structured to receive a second signal indicative of a downstream air-fuel equivalence ratio from a second sensor positioned downstream of the intake of the catalyst, adjust the duty cycle based at least in part on the second signal, and provide a fault signal in response to the duty cycle not meeting a duty cycle range for a predetermined period of time. The apparatus also includes a notification circuit structured to provide a notification indicating that the second sensor is faulty in response to receiving the fault signal.

[0008] Another embodiment relates to an apparatus that includes a processing circuit structured to receive a first signal indicative of an upstream air-fuel equivalence ratio from a first sensor positioned upstream of an intake of a catalyst, receive a second signal indicative of a downstream air-fuel equivalence ratio from a second sensor positioned downstream of the intake of the catalyst, provide a control signal to an engine to produce a desired first signal, predict an expected second signal based at least in part on the desired first signal, compare the first signal to the desired first signal, determine a second signal differential between the second signal and the expected second signal when the first signal is equal to the desired first signal, and provide a fault signal in response to the second signal differential exceeding a threshold differential. The apparatus also includes a notification circuit structured to provide a notification indicating that the second sensor is faulty in response to receiving the fault signal.

[0009] Another embodiment relates to an apparatus that includes a processing circuit structured to receive a key-on or key-off signal from an ignition circuit, provide a fuel cut or lean run signal to an engine, receive a lambda signal indicative of a downstream air-fuel equivalence ratio from a sensor positioned downstream of an intake of a catalyst, and provide a fault signal in response to the lambda signal indicating the downstream air-fuel equivalence ratio is less than one. The apparatus also includes a notification circuit structured to provide a notification indicating that the sensor is faulty in response to receiving the fault signal.

[0010] These and other features, together with the organization and manner of operation thereof, will become apparent from the following detailed description when taken in conjunction with the accompanying drawings.

Description

BRIEF DESCRIPTION OF THE FIGURES

[0011] FIG. **1** is schematic diagram of an exhaust aftertreatment system with a controller, according to an example embodiment.

[0012] FIG. **2** is a schematic diagram of the controller used with the exhaust aftertreatment system of FIG. **1**, according to an example embodiment.

[0013] FIG. **3** is a flow chart illustrating a method of diagnosing a stuck exhaust gas oxygen sensor (EGO), according to an example embodiment.

[0014] FIG. **4** is a graph illustrating a first lambda associated with a first EGO sensor and a second lambda associated with a second EGO sensor over time during operation of the method of FIG. **3**, according to an example embodiment.

[0015] FIG. **5** is a graph illustrating a first lambda associated with a first EGO sensor and a second lambda associated with a second EGO sensor over time during operation of the method of FIG. **3**, according to an example embodiment.
[0016] FIG. **6** is a flow chart illustrating a method of diagnosing a stuck EGO sensor, according to an example embodiment.
[0017] FIG. **7** is a graph illustrating a first lambda associated with a first EGO sensor and a second lambda associated with a second EGO sensor over time during operation of the method of FIG. **6**, according to an example embodiment.
[0018] FIG. **8** is a graph showing a first lambda associated with a first EGO sensor and a second lambda associated with a second EGO sensor over time during operation of the method of FIG. **6**, according to an example embodiment.
[0019] FIG. **9** is a schematic illustration of feedback loops used by the exhaust aftertreatment system of FIG. **1**, according to an example embodiment.
[0020] FIG. **10** is a flow chart illustrating a method of diagnosing a stuck EGO sensor, according to an example embodiment.
[0021] FIG. **11** is a graph showing a first lambda associated with a first EGO sensor and a second lambda associated with a second EGO sensor over time during operation of the method of FIG. **10**, according to an example embodiment.
[0022] FIG. **12** is a flow chart illustrating a method of diagnosing a stuck EGO sensor, according to an example embodiment.
[0023] FIG. **13** is a flow chart illustrating a method of diagnosing a stuck EGO sensor, according to an example embodiment.

DETAILED DESCRIPTION

[0024] Following below are more detailed descriptions of various concepts related to, and implementations of, methods, apparatuses, and systems for model based catalyst diagnostics. The various concepts introduced above and discussed in greater detail below may be implemented in any number of ways, as the concepts described are not limited to any particular manner of implementation. Examples of specific implementations and applications are provided primarily for illustrative purposes.
[0025] Referring the figures generally, the various embodiments disclosed herein relate to systems, apparatuses, and methods for operating an engine system and monitoring or diagnosing a stuck catalyst sensor of an exhaust aftertreatment system (e.g., a three-way catalyst). The engine system includes an internal combustion engine that in one embodiment is a spark-ignition engine. In other embodiments, another engine type making use of stoichiometric combustion may be used. For example, a compression-ignition engine (e.g., a diesel engine) may be arranged to operate using an exhaust aftertreatment system as described herein. The engine system also includes an engine exhaust pipe that provides engine exhaust gases to a catalyst. A catalyst exhaust pipe is connected to the catalyst and provides treated exhaust gas to a muffler or another component of the exhaust aftertreatment system. An engine control system includes a controller, a first exhaust gas oxygen sensor (EGO) arranged to sense a condition of the engine exhaust gas, and a second (or secondary) EGO arranged to sense a condition of the treated exhaust gas. In order to regulate a proper Air-Fuel Ratio to the catalyst or diagnose the catalyst for malfunction, the second EGO sensor may be located downstream of the three-way catalyst or at any location upstream such that there is a volume of the catalyst between the second EGO sensor and the first EGO sensor. The EGO sensors may be heated or unheated, or of a narrow-band (i.e., switching) or wide-band type of sensor.
[0026] The controller receives lambda signals from the first EGO sensor and the second EGO sensor indicative of an air:fuel equivalence ratio (lambda λ). When lambda λ is less than one (1), the lambda signal indicates that the air:fuel mixture in the exhaust gas is rich. When the lambda λ is greater than one (1), the lambda signal indicates that the air:fuel mixture in the exhaust gas is lean. A lambda signal of one (1) indicates stoichiometric balance. Comparisons of a first lambda signal

received from the first EGO sensor and a second lambda signal received from the second EGO sensor can be used to diagnose various attributes and faults of the catalyst and the first and second EGO sensors.

[0027] Within this document, the term motoring, exit motoring, and dithering describe three operational conditions of the engine that occur in response to user (e.g., a driver) input. Motoring occurs when no fuel is being provided to the engine. For example, motoring may occur when the user is braking, coasting downhill, or when a gear shift is occurring. Typically, motoring occurs in a passenger or commercial vehicle for between one and fifteen seconds for any given motoring condition, though other time periods occur more occasionally. During a motoring condition, the exhaust gas will be lean. Exit motoring occurs when the user causes fuel to be provided to the engine directly following a motoring condition. The exit motoring condition may last between one and two seconds, or may be longer. During the exit motoring condition, extra fuel is provided to the engine to quickly enrich the catalyst and desorb excess oxygen from the catalyst. Dithering occurs during normal operation of the engine when fuel is being provided. In the dithering condition, the air:fuel mixture of the exhaust gas will alternate between rich and lean.

[0028] The engine control system monitors the catalyst to confirm that the catalyst is functioning properly and also monitors the EGO sensors to confirm that the EGO sensors are not stuck or otherwise faulty. In one embodiment, the controller sets a baseline oxygen storage capacity of the catalyst corresponding to a new catalyst. Then, using the first EGO sensor and the second EGO sensor, a current storage capacity is determined. If the current storage capacity is determined to be larger than the baseline storage capacity, the controller indicates that one of the first and second EGO sensors is stuck (i.e., indicating a lean or rich lambda λ inaccurately).

[0029] In another embodiment, the controller monitors the first lambda signal received from the first EGO sensor and the second lambda signal received from the second EGO sensor over time. The controller determines a first median lambda of the first lambda signal, and a second median lambda of the second lambda signal. The controller then determines a median differential between the first median lambda and the second median lambda. Over time, the controller continues to determine and monitor the median differential. If the median differential exceeds a predetermined threshold value, then the controller indicates that one of the first and second EGO sensors is stuck.

[0030] In another embodiment, the first EGO sensor is arranged at an inlet of the catalyst and the second EGO sensor is arranged downstream of the inlet of the catalyst. The controller controls the air:fuel ratio provided to the engine based at least in part on a duty cycle of the first EGO sensor. The duty cycle is defined by the dithering of the first lambda signal as it switches between indicating a lean and rich air:fuel mixture over time. A normally operating engine system will operate at about a 50% duty cycle. In other words, the first lambda signal will indicate that the air:fuel mixture is rich about half the time, and lean about half the time. In some embodiments, it is preferred to run slightly rich at a 55% duty cycle indicating that the air:fuel mixture is rich 55% of the time, and lean 45% of the time. In other embodiments, different duty cycles may be desired and enacted by the engine system, as desired. If the controller determines that the duty cycle is operating outside of an acceptable duty cycle range for a predetermined amount of time, the controller indicates that one of the first and second EGO sensors is stuck. In some embodiments, the acceptable duty cycle range may be between 30% and 70% and the predetermined time is 10 seconds. In other embodiments, the acceptable duty cycle range may be between 10% and 90% and the predetermined time may be 5 seconds.

[0031] In another embodiment, the controller monitors the second EGO sensor and a prompt condition enables an intrusive stuck sensor check. The prompt condition may be an indication that the second EGO sensor is stuck according to one of the above schemes or another prompt condition such as initial engine start up. The intrusive stuck sensor check includes operating the engine at a known condition (e.g., providing a rich mixture if the second EGO sensor is stuck lean, or a lean mixture if the second EGO sensor is stuck rich). After a predetermined amount of time (e.g., 10 seconds) if the second EGO sensor has not reacted to the known condition (e.g., switching to lean or rich), then the controller indicates that the second EGO sensor is stuck.

[0032] In another embodiment, the controller checks if the second EGO sensor is stuck rich during a key-on or key-off operation. During key-on and key-off events, the catalyst should have time to fully absorb oxygen, and the reading of the second EGO sensor should therefore always indicate a lean air:fuel mixture. If the controller receives a second lambda signal indicating a rich air:fuel mixture, the controller indicates that the second EGO sensor is stuck.

[0033] As shown in FIG. **1**, an engine system **20** includes an engine **24**, an engine exhaust pipe **28** that receives engine exhaust gases from the engine **24**, a catalytic converter **32** including a catalyst **36** that receives the engine exhaust gas from the engine exhaust pipe **28** and treats the engine exhaust gases, a catalyst exhaust pipe **40** that receives the treated exhaust gases from the catalytic converter **32**, and a downstream component **44** such as a muffler or another aftertreatment component. The engine system **20** also includes an engine control system **48** that includes a controller **52**, a first exhaust gas oxygen sensor (EGO) **56** that communicates with the controller **52** and is positioned to detect a characteristic of the engine exhaust gas upstream on an inlet to the catalyst **36**, and a second EGO **60** that communicates with the controller **52** and is positioned to detect a characteristic of the treated exhaust gas at a point downstream of the inlet of the catalyst **36**. In one embodiment, the catalytic converter **32** is part of a larger exhaust aftertreatment system that may include the controller **52** and the sensors **56**, **60** as well as other components.

[0034] The engine **24** can be an internal combustion engine such as a spark-ignition engine fueled by gasoline, natural gas, ethanol, propane, or another fuel suitable for spark-ignition. The engine **24** can be a compression-ignition engine fueled by diesel, or another fuel suitable for compression-ignition. The engine **24** can include a combustion chamber and an exhaust port or manifold that couples to the engine exhaust pipe **28** to contain the engine exhaust gases. Many designs and arrangements of engines and engine exhaust pipes may be used with the embodiments described herein and the engine and engine exhaust pipe shown and described are to be construed as non-limiting examples.

[0035] In one embodiment, the catalytic converter **32** includes a three-way catalyst **36** and is intended to be used with spark-ignition engines. In another embodiment, the catalyst may be a two-way catalyst intended to be used with a compression-ignition engine, or another type of catalyst that benefits from a monitoring system.

[0036] The catalyst exhaust pipe **40** and the downstream component **44** receive the treated exhaust gases from the catalytic converter **32** and may perform other emissions treatment steps, and may muffle the noise of the engine **24**. The arrangement of the catalyst exhaust pipe **40** and the downstream component **44** are non-limiting examples.

[0037] As shown in FIG. **2**, the controller **52** includes a processing circuit **64** and a communication interface **68** structured to communicate with the first EGO **56**, the second EGO **60**, the engine **24**, and a display **72**. The communication interface **68** may receive a first lambda signal from the first EGO **56**, a second lambda signal from the second EGO **60**, the engine signals from the engine **24**, provide operation instructions to the engine **24** that cause the engine to perform a specific action (e.g., inject more or less fuel), and provide display or alert information to the display **72**. In one embodiment, the display **72** is a data port on the engine **24** or in a vehicle associated with the engine **24**.

[0038] The processing circuit **64** includes a processor **76**, a memory **80**, and a diagnostic circuit **84**. The processor **76** can include a notification circuit, and may be implemented as a general-purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a digital signal processor (DSP), a group of processing components, or other suitable electronic processing components. The memory **80** (e.g., RAM, ROM, Flash Memory, hard disk storage, etc.) may store data and/or computer code for facilitating the various processes described herein. The memory **80** may be communicably connected to the processor **76**, the diagnostic circuit **84**, and the communication interface **68** and structured to provide computer code or instructions to the processor **76** for executing the processes described in regard to the controller **52**. Additionally, the memory **80** may be or include tangible, non-transient volatile memory or non-volatile memory. Accordingly, the memory **80** may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described herein.

[0039] The diagnostic circuit **84** includes various circuits (e.g., processor and memory circuits having executable code stored therein) for completing the activities described herein. More particularly, the diagnostic circuit **84** includes circuits structured to operate components of the engine **24** and the aftertreatment system. While various circuits with particular functionality are shown in FIG. **2**, it should be understood that the controller **52**, memory **80**, and diagnostic circuit **84** may include any number of circuits for completing the functions described herein and that any number of the circuits described may be combined into a single circuit. For example, the activities and functionalities of the circuits of the diagnostic circuit **84** may be embodied in the memory **80**, or combined in multiple circuits or as a single circuit. Additional circuits with additional functionality may be included. Further, it should be understood that the controller **52** may further control other vehicle activity beyond the scope of the present disclosure.

[0040] The diagnostic circuit **84** includes an engine circuit **88** structured to control various operations of the engine **24** as well as communicate with various sensors arranged in the engine **24**; a fuel circuit **92** structured to monitor an amount of fuel provided to the engine **24** or a characteristic of the fuel provided to the engine **24**; an oxygen in circuit **96** structured to communicate with the first EGO **56** and to analyze the first lambda signal; an oxygen out circuit **100** structured to communicate with the second EGO **60** and to analyze the second lambda signal; a lambda circuit **104** structured to communicate with the engine circuit **88**, the fuel circuit **92**, the oxygen in circuit **96**, and the oxygen out circuit **100** and to analyze the received signals; a timer circuit **112**; and an oxygen storage circuit **116** structured to communicate with the lambda circuit **104** and the timer circuit **112** to analyze a response of the catalyst **36** to engine operation.

[0041] As shown in FIG. **3**, a method **118** of determining a stuck EGO sensor includes determining a maximum storage capacity of the catalyst **36** in step **120**. The maximum storage capacity corresponds to the amount of oxygen that a new catalyst **36** can hold. Over the life span of the catalyst **36**, the oxygen storage capacity of the catalyst **36** will decrease, so the maximum storage capacity represents the actual maximum amount of oxygen that the catalyst **36** will ever be able to hold in reality. In some embodiments, determining the maximum storage capacity includes querying the memory **80** with the oxygen storage circuit **116** to identify a predetermined or saved maximum storage capacity. In some embodiments, the memory **80** is a database that is located within the controller **52**. In some embodiments, the database is located remotely from the controller **52** and may be queried by the controller **52** to determine the maximum storage capacity. In some embodiments, the maximum storage capacity is determined by the oxygen storage circuit **116** when the catalyst **36** is first installed. In some embodiments, the determination of the maximum storage capacity of oxygen is based at least in part on an oxygen flux flowing through the catalyst **36** as determined by the first EGO **56** and the second EGO **60**, and the oxygen in circuit **96** and the oxygen out circuit **100**. In one embodiment, the maximum oxygen capacity is about ten grams (10 g). In other embodiments, the maximum storage capacity is between about seven grams and about thirteen grams (7-13 g). It will be appreciated that other maximum storage capacities are possible for other catalysts.

[0042] Once the maximum storage capacity is determined, the controller **52** determines the operational condition of the engine **24** at step **124** by communicating with the fuel circuit **92** and the engine circuit **88**. If the fuel circuit **92** determines that no fuel is being provided to the engine **24** and the engine circuit **88** determines that the engine **24** is still running, then the controller **52** determines that the engine **24** is in a motoring condition. If the fuel circuit **92** determines that fuel is being provided to the engine **24**, the engine circuit **88** determines that the engine **24** is still running, and the controller **52** recognizes that the previous operating condition was a motoring condition, then the controller **52** determines that the engine **24** is in an exit motoring condition.

[0043] If the controller **52** determines the engine **24** is in a motoring condition, then the first EGO **56** and the second EGO **60** are monitored at step **128**. During monitoring, the first lambda signal is received by the oxygen in circuit **96** and the second lambda signal is received by the oxygen out circuit **100**, and the first lambda signal and the second lambda signal are processed by the lambda circuit **104** to determine a first lambda λ.sub.1 indicative of the air:fuel mixture sensed by the first EGO **56** and a second lambda λ.sub.2 indicative of the air:fuel mixture sensed by the second EGO **60**.

[0044] At step **132**, the first lambda λ.sub.1 experiences a first lean breakthrough. At step **136**, the second lambda λ.sub.2 experiences a second lean breakthrough. The oxygen storage circuit **116** communicates with the lambda circuit **104** and the timer circuit **112** to identify the first lean breakthrough and the second lean breakthrough. At step **142**, the oxygen storage circuit **116** determines an actual storage capacity of the catalyst **36** based on the first lean breakthrough and the second lean breakthrough. The actual storage capacity may be calculated at least in part on the timing of the second lean breakthrough relative to the first lean breakthrough.

[0045] FIG. **4** illustrates the first lambda λ.sub.1 and the second lambda λ.sub.2 experiencing lean breakthroughs at different times. The first lean breakthrough is indicated as occurring at time **132** corresponding to step **132** and the second lean breakthrough is indicated as occurring at time **136** corresponding to step **136**. The actual storage capacity is indicated at **142** as the integral between the first lean breakthrough and the second lean breakthrough.

[0046] As shown in FIG. **3**, at step **146**, the oxygen storage circuit **116** compares the actual oxygen storage capacity to the maximum storage capacity. If the actual storage capacity is greater than the maximum storage capacity, a fault notification is generated at step **150** and a notification is sent from the communication interface **68** to the display **72** to alert the user that the second EGO **60** is stuck rich. In one embodiment, the fault notification is generated if the actual storage capacity greater than the maximum storage capacity by a threshold value. In some embodiments, the threshold value is about five times the maximum storage capacity (i.e., threshold value=5×maximum storage capacity). In some embodiments, the threshold value is a fixed value (e.g., fifty grams). If the actual storage capacity is not greater than the maximum storage capacity, then the method returns to step **124**.

[0047] If the controller **52** determines that the engine **24** is in the exit motoring condition at step **124**, then the first EGO **56** and the second EGO **60** are monitored at step **154**. At step **158**, the first lambda λ.sub.1 experiences a first rich breakthrough. At step **162**, the second lambda λ.sub.2 experiences a second rich breakthrough. The oxygen storage circuit **116** communicates with the lambda circuit **104** and the timer circuit **112** to identify the first rich breakthrough and the second rich breakthrough. At step **166**, the oxygen storage circuit **116** determines an actual storage capacity of the catalyst **36** based on the first rich breakthrough and the second rich breakthrough. The actual storage capacity may be calculated at least in part on the timing of the second rich breakthrough relative to the first rich breakthrough.

[0048] FIG. **5** illustrates the first lambda λ.sub.1 and the second lambda λ.sub.2 experiencing rich breakthroughs at different times. The first rich breakthrough is indicated as occurring at time **158** corresponding to step **158** and the second rich breakthrough is indicated as occurring at time **162** corresponding to step **162**. The actual storage capacity is indicated at **166** as the integral between the first rich breakthrough and the second rich breakthrough.

[0049] As shown in FIG. **3**, at step **170**, the oxygen storage circuit **116** compares the actual oxygen storage capacity to the maximum storage capacity. If the actual storage capacity is greater than the maximum storage capacity, a fault notification is generated at step **174** and a notification is sent from the communication interface **68** to the display **72** to alert the user that the second EGO **60** is stuck lean. If the actual storage capacity is not greater than the maximum storage capacity, then the method returns to step **124**.

[0050] As shown in FIG. **6**, a method **176** of determining a stuck EGO sensor includes monitoring the first EGO **56** and the second EGO **60** and determining the first lambda λ.sub.1 and the second lambda λ.sub.2 with the lambda circuit **104** at step **178**. At step **182**, a first statistically metric is determined by the controller **52** based on the first lambda λ.sub.1. In some embodiments, the first statistical metric is a median lambda value (e.g., 1.4 would indicate a lean median, 0.5 would indicate a rich median). In some embodiments, the first statistical metric is a mean lambda value. In some embodiments another statistic metric may be used, such as a duty cycle. At step **186**, a second statistical metric is determined by the controller **52** based on the second lambda λ.sub.2. The second statistical metric is the same as the first statistical metric (e.g., median, mean, duty cycle).

[0051] In some embodiments, a first variability of the first statistical metric is determined by the controller **52** at step **190** and a second variability of the second statistical metric is determined by the controller **52** at step **194**. The first variability and the second variability may be statistical tools such as standard deviations, bandwidth calculations, or other variability measures, as desired.

[0052] At step **198**, a statistical metric differential is determined by the controller **52** by comparing the first statistical metric to the second statistical metric. At step **202**, the statistical metric differential is compared to a predetermined threshold. If the statistical metric differential is less than the predetermined threshold, then the method returns to step **178** and continues monitoring. In some embodiments, the controller **52** also compares the first variability to the second variability at step **206**, and if the second variability is not less than the first variability, then the method returns to step **178** and continues monitoring.

[0053] If the controller **52** determines at step **202** that the statistical metric differential is greater than the predetermined threshold, then the controller **52** checks the engine **24** to determine the operational condition at step **210**. In some embodiments, the controller **52** verifies that the second variability is less than the first variability before progressing to step **210**. In other embodiments, the variability comparison of step **206** replaces step **202**.

[0054] If the controller **52** determines at step **210** that the engine **24** is operating in the motoring condition, then a fault notification is generated at step **214** and a notification is sent from the communication interface **68** to the display **72** to alert the user that the second EGO **60** is stuck rich. If the controller **52** determines at step **210** that the engine **24** is operating in the dithering condition, then a fault notification is generated at step **218** and a notification is sent from the communication interface **68** to the display **72** to alert the user that the second EGO **60** is stuck lean.

[0055] As shown in FIG. **7**, the method **176** monitors the first lambda λ.sub.1 and the second lambda λ.sub.2 over time. The first statistical metric is based at least in part on the stoichiometric breakthroughs of the first lambda signal and the second lambda signal. The first statistical metric is shown as a median over time at line **182** corresponding to step **182**, while the second statistical metric is shown as a median over time at line **186** corresponding to step **186**. If the controller **52** determines at step **202** that the differential between the median shown at line **186** and the median shown at line **182** is greater that the predetermined threshold, a fault signal is generated. FIG. **7** illustrates an example of the second EGO **60** stuck rich.

[0056] As shown in FIG. **8**, the first variability (shown as range **190** corresponding to step **190**) can be measured over a predetermined amount of time, and the second variability (shown as range **194** corresponding to step **194**) can be measured over the same predetermined amount of time. If the second EGO **60** is functioning normally, the second lambda signal should indicate a larger variability in the second lambda λ.sub.2 than the first lambda λ.sub.1. If the second lambda λ.sub.2 has a smaller variability than the first lambda λ.sub.1 then the second EGO **60** is stuck and not reading accurately. FIG. **8** illustrates an example of the second EGO **60** stuck lean.

[0057] As shown in FIG. **9**, the engine **24** is controlled by the controller **52** at least in part based on a primary feedback loop **222** communicating with the first EGO **56**, a secondary feedback loop **226** communicating with the second EGO **60**, and a fault diagnostic method **230**. The fault diagnostic method **230** is based on a duty cycle of the first lambda λ.sub.1 determined by the lambda circuit **104**. The primary feedback loop **222** is used to control the engine **24** to achieve a stoichiometric balance at the inlet to the catalyst **36**. In other words, the controller **52** sends control signals to the engine **24** such that the first lambda λ.sub.1 is one or another desired value (e.g., 0.95). The secondary feedback loop **226** is also used to control the engine **24** but the variability of the second lambda λ.sub.2 is larger and the control signal sent to the engine **24** from the controller **52** accounts for corrective action or secondary controls based on the second feedback loop **226**, rather than the primary control provided by the primary feedback loop **222**.

[0058] As shown in FIG. **10**, the method **230** first determines that the engine **24** is operating in the dithering condition with the controller **52** at step **234**. If the engine **24** is operating in a dithering condition, then the first EGO **56** is monitored at step **238**. The oxygen in circuit **96** receives the first lambda signal, and the lambda circuit **104** determines the first lambda λ.sub.1. Then the controller **52** sends a primary control signal (i.e., the primary feedback loop **222**) to the engine **24** to maintain the first lambda λ.sub.1 at a desired control lambda (e.g., 1.0, 0.95) at step **242**.

[0059] The second EGO **60** is monitored concurrently at step **246**, and the oxygen out circuit **100** receives the second lambda signal. The lambda circuit **104** then determines the second lambda λ.sub.2. Then the controller **52** sends a secondary control signal (i.e., the secondary feedback loop **226**) to the engine **24** to maintain the second lambda λ.sub.2 within a desired lambda range (e.g., between 0.5 and 1.5) at step **250**.

[0060] At step **254**, the fault diagnostic **230** of the controller **52** determines a duty cycle of the first lambda λ.sub.1. As discussed above, the duty cycle is indicative of a rich:lean ratio over time. During normal operation, the duty cycle will correspond to the desired control lambda (e.g., 50% duty cycle, 52% duty cycle). At step **258**, the duty cycle is compared to a duty cycle range. The duty cycle range is a predetermined range of duty cycle values that indicate normal operation. In some embodiments, the duty cycle range is between about 40% and about 60%. In some embodiments, the duty cycle range is between about 30% and about 70%. In some embodiments, the duty cycle range is between about 10% and about 90%. If the duty cycle is determined to be less than the duty cycle range at step **258**, then a fault notification is generated at step **262** and a notification is sent from the communication interface **68** to the display **72** to alert the user that the second EGO **60** is stuck rich.

[0061] If the duty cycle is determined to be greater than the duty cycle range at step **266**, then a fault notification is generated at step **270** and a notification is sent from the communication interface **68** to the display **72** to alert the user that the second EGO **60** is stuck lean.

[0062] The method **230** takes advantage of the control signals based on the primary feedback loop **222** and the secondary feedback loop **226** to diagnose the second EGO **60**. If the second EGO **60** is stuck rich, it will continually cause the secondary control signal sent by the controller **52** to instruct the engine **24** to run lean. This in turn will cause the duty cycle of the first EGO **56** to drop outside the duty cycle range (e.g., the duty cycle drops to 25%). This drop in duty cycle will be recognized at step **258**, and the controller **52** will indicate that the second EGO **60** is stuck rich. If the second EGO **60** is stuck lean, it will continually cause the secondary control signal sent by the controller **52** to instruct the engine **24** to run rich. This in turn will cause the duty cycle of the first EGO **56** to rise outside the duty cycle range (e.g., the duty cycle rises to 75%). This rise in duty cycle will be recognized at step **266**, and the controller **52** will indicate that the second EGO **60** is stuck lean.

[0063] FIG. **11** illustrates an example of a second EGO **60** that is stuck lean causing the duty cycle to skew rich (e.g., 75%). This shift in duty cycle is recognized by the controller **52** at step **266** and a notification is sent to the display **72** indicating that the second EGO **60** is stuck lean.

[0064] As shown in FIG. **12**, a method **274** of determining a stuck EGO sensor includes monitoring the first EGO **56** and the second EGO **60** with the controller **52** at step **278**. During monitoring, the oxygen in circuit **96** receives the first lambda signal, and the lambda circuit **104** determines the first lambda λ.sub.1, and the oxygen out circuit **100** receives the second lambda signal, and the lambda circuit **104** determines the second lambda λ.sub.2.

[0065] At step **282**, the controller **52** develops a desired first lambda λ.sub.1,D and sends a first control signal to the engine **24** to produce the desired first lambda λ.sub.1,D as measured by the first EGO **56** at step **286**. Based on the desired first lambda λ.sub.1,D, the controller **52** develops an expected or a predicted second lambda λ.sub.2,P at step **290**.

[0066] The controller **52** then continues to monitor the first EGO **56** and the second EGO **60**, and compares the first lambda λ.sub.1 to the desired first lambda λ.sub.1,D at step **294** until the first lambda λ.sub.1 is equal to the desired first lambda λ.sub.1,D and has reached steady state. Once the first lambda λ.sub.1 equals desired first lambda λ.sub.1,D and has reached steady state, the controller determines a second signal differential between the second lambda λ.sub.2 and the predicted second lambda λ.sub.2,P at step **298**.

[0067] At step **302**, the controller **52** compares the second signal differential to a threshold differential. If the second signal differential is less than the threshold differential, the method **274** returns to step **278** and continues monitoring. If the second signal differential is not less than the threshold differential, a fault notification is generated at step **306** and a notification is sent from the communication interface **68** to the display **72** to alert the user that the second EGO **60** is stuck. In some embodiments, the threshold differential is about 0.7. In some embodiments, the threshold differential is about 0.5. In some embodiments, the controller **52** uses an absolute value for the second signal differential for comparison to the threshold differential. In some embodiments, the value of the second lambda λ.sub.2 is used to determine if the second EGO **60** is stuck rich or lean.

[0068] In one example, the first control signal instructs the engine **24** to run rich to achieve a desired first lambda λ.sub.1,D of about 0.5. The predicted second lambda λ.sub.2,P is about 0.6. The controller **52** then determines that the actual second lambda λ.sub.2 is about 1.3 and that the second signal differential is about 0.7. The controller **52** compares the second signal differential to the threshold differential of 0.5 and identifies that the second EGO **60** is stuck. The controller **52** may also identify that the second EGO **60** is stuck lean because the second lambda λ.sub.2 is greater than one. The notification is the sent to the display **72** indicating that the second EGO **60** is stuck lean.

[0069] As shown in FIG. **13**, a method **310** provides a diagnostic solution for the second EGO **60** at key-on and key-off conditions. For example, a user first starting the engine **24** may be considered a key-on condition, and the engine **24** being shut off or stopped may be considered a key-off condition. At step **314**, the controller **52** recognizes a key-on or a key-off condition. At step **318**, the controller **52** sends a control signal to the engine **24** to operate in one of a fuel cut or a run lean condition. In the case of a key-on condition, the controller **52** may check to determine an off time (e.g., via communication with the timer circuit **112**) since the last key-off condition. If the off time is equal to or greater than a predetermined rest time, the controller **52** assumes that the catalyst **36** has had time to fully oxidize or adsorb a full storage capacity of oxygen and sends the control signal to operate the engine **24** in a run lean condition. In the case of a key-off condition, the controller **52** sends the signal to operate the engine **24** in a fuel cut condition for a predetermined fuel cut time intended to provide the catalyst **36** adequate time to fully oxidize or adsorb a full storage capacity of oxygen. After the control signal is sent at step **318**, the controller **52** monitors the second EGO **60** at step **322**.

[0070] At step **326**, the controller **52** compares the second lambda λ.sub.2 to a stoichiometric balance (e.g., 1.0). If the second lambda λ.sub.2 is greater than the stoichiometric balance, then the controller **52** indicates that the second EGO **60** is stuck rich and a fault notification is generated at step **330** and a notification is sent from the communication interface **68** to the display **72** to alert the user that the second EGO **60** is stuck rich. If the second lambda λ.sub.2 is equal to or less than the stoichiometric balance, then the controller **52** operates the engine **24** normally, either by continuing to run, or stopping at step **334**.

[0071] It should be understood that no claim element herein is to be construed under the provisions of 35 U.S.C. § 112(f), unless the element is expressly recited using the phrase "means for." The schematic flow chart diagrams and method schematic diagrams described above are generally set forth as logical flow chart diagrams. As such, the depicted order and labeled steps are indicative of representative embodiments. Other steps, orderings, and methods may be conceived that are equivalent in function, logic, or effect to one or more steps, or portions thereof, of the methods illustrated in the schematic diagrams. Further, reference throughout this specification to "one embodiment", "an embodiment", "an example embodiment", or similar language means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases "in one embodiment", "in an embodiment", "in an example embodiment", and similar language throughout this specification may, but do not necessarily, all refer to the same embodiment.
[0072] Additionally, the format and symbols employed are provided to explain the logical steps of the schematic diagrams and are understood not to limit the scope of the methods illustrated by the diagrams. Although various arrow types and line types may be employed in the schematic diagrams, they are understood not to limit the scope of the corresponding methods. Indeed, some arrows or other connectors may be used to indicate only the logical flow of a method. For instance, an arrow may indicate a waiting or monitoring period of unspecified duration between enumerated steps of a depicted method. Additionally, the order in which a particular method occurs may or may not strictly adhere to the order of the corresponding steps shown. It will also be noted that each block of the block diagrams and/or flowchart diagrams, and combinations of blocks in the block diagrams and/or flowchart diagrams, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and program code.
[0073] Many of the functional units described in this specification have been labeled as circuits, in order to more particularly emphasize their implementation independence. For example, a circuit may be implemented as a hardware circuit comprising custom very-large-scale integration (VLSI) circuits or gate arrays, off-the-shelf semiconductors such as logic chips, transistors, or other discrete components. A circuit may also be implemented in programmable hardware devices such as field programmable gate arrays, programmable array logic, programmable logic devices or the like.
[0074] As mentioned above, circuits may also be implemented in machine-readable medium for execution by various types of processors. An identified circuit of executable code may, for instance, comprise one or more physical or logical blocks of computer instructions, which may, for instance, be organized as an object, procedure, or function. Nevertheless, the executables of an identified circuit need not be physically located together, but may comprise disparate instructions stored in different locations which, when joined logically together, comprise the circuit and achieve the stated purpose for the circuit. Indeed, a circuit of computer readable program code may be a single instruction, or many instructions, and may even be distributed over several different code segments, among different programs, and across several memory devices. Similarly, operational data may be identified and illustrated herein within circuits, and may be embodied in any suitable form and organized within any suitable type of data structure. The operational data may be collected as a single data set, or may be distributed over different locations including over different storage devices, and may exist, at least partially, merely as electronic signals on a system or network.
[0075] The computer readable medium (also referred to herein as machine-readable media or machine-readable content) may be a tangible computer readable storage medium storing the computer readable program code. The computer readable storage medium may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, holographic, micromechanical, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. As alluded to above, examples of the computer readable storage medium may

include but are not limited to a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a portable compact disc read-only memory (CD-ROM), a digital versatile disc (DVD), an optical storage device, a magnetic storage device, a holographic storage medium, a micromechanical storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage medium may be any tangible medium that can contain and/or store computer readable program code for use by and/or in connection with an instruction execution system, apparatus, or device.

[0076] The computer readable medium may also be a computer readable signal medium. A computer readable signal medium may include a propagated data signal with computer readable program code embodied therein, for example, in baseband or as part of a carrier wave. Such a propagated signal may take any of a variety of forms, including, but not limited to, electrical, electro-magnetic, magnetic, optical, or any suitable combination thereof. A computer readable signal medium may be any computer readable medium that is not a computer readable storage medium and that can communicate, propagate, or transport computer readable program code for use by or in connection with an instruction execution system, apparatus, or device. As also alluded to above, computer readable program code embodied on a computer readable signal medium may be transmitted using any appropriate medium, including but not limited to wireless, wireline, optical fiber cable, Radio Frequency (RF), or the like, or any suitable combination of the foregoing. In one embodiment, the computer readable medium may comprise a combination of one or more computer readable storage mediums and one or more computer readable signal mediums. For example, computer readable program code may be both propagated as an electro-magnetic signal through a fiber optic cable for execution by a processor and stored on RAM storage device for execution by the processor.

[0077] Computer readable program code for carrying out operations for aspects of the present invention may be written in any combination of one or more programming languages, including an object oriented programming language such as Java, Smalltalk, C++ or the like and conventional procedural programming languages, such as the “C” programming language or similar programming languages. The computer readable program code may execute entirely on the user's computer, partly on the user's computer, as a stand-alone computer-readable package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

[0078] The program code may also be stored in a computer readable medium that can direct a computer, other programmable data processing apparatus, or other devices to function in a particular manner, such that the instructions stored in the computer readable medium produce an article of manufacture including instructions which implement the function/act specified in the schematic flowchart diagrams and/or schematic block diagrams block or blocks.

[0079] Accordingly, the present disclosure may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the disclosure is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

Claims

1. An apparatus comprising: a processing circuit structured to: receive a first signal indicative of an upstream air-fuel equivalence ratio from a first sensor positioned upstream of an intake of a catalyst; receive a second signal indicative of a downstream air-fuel equivalence ratio from a second sensor positioned downstream of the intake of the catalyst; provide a control signal to an engine to produce a desired first signal; predict an expected second signal based at least in part on the desired first signal; compare the first signal to the desired first signal; determine a second signal differential between the second signal and the expected second signal when the first signal is equal to the desired first signal; and provide a fault signal in response to the second signal differential exceeding a threshold differential; and a notification circuit structured to provide a notification indicating that the second sensor is faulty in response to receiving the fault signal.
2. The apparatus of claim 1, wherein providing the control signal causes more fuel to be injected into the engine, and the desired first signal is indicative of an air-fuel equivalence ratio of less than one.
3. The apparatus of claim 2, wherein the expected second signal is indicative of an air-fuel equivalence ratio of less than one.
4. The apparatus of claim 1, wherein providing the control signal causes more fuel to be injected into the engine, and the desired first signal is indicative of an air-fuel equivalence ratio of greater than one.
5. The apparatus of claim 4, wherein the expected second signal is indicative of an air-fuel equivalence ratio of greater than one.
6. The apparatus of claim 1, wherein the fault signal is only provided during a dithering mode.
7. The apparatus of claim 1, wherein the processing circuit determines the second signal differential when the upstream air-fuel equivalence ratio indicated by the first signal is maintained within a predefined value.
8. The apparatus of claim 1, wherein the processing circuit is further structured to determine, using the second signal, that the second sensor is stuck rich or stuck lean, and wherein the notification indicates that the second sensor is stuck rich or stuck lean based on the determination.
9. A method comprising: receiving a first signal indicative of an upstream air-fuel equivalence ratio from a first sensor positioned upstream of an intake of a catalyst; receiving a second signal indicative of a downstream air-fuel equivalence ratio from a second sensor positioned downstream of the intake of the catalyst; providing a control signal to an engine to produce a desired first signal; predicting an expected second signal based at least in part on the desired first signal; comparing the first signal to the desired first signal; determining a second signal differential between the second signal and the expected second signal when the first signal is equal to the desired first signal; and providing a fault signal in response to the second signal differential exceeding a threshold differential.
10. The method of claim 9, wherein providing the control signal causes more fuel to be injected into the engine, and wherein the desired first signal is indicative of an air-fuel equivalence ratio of less than one.
11. The method of claim 10, wherein the expected second signal is indicative of an air-fuel equivalence ratio of less than one.
12. The method of claim 9, wherein providing the control signal causes more fuel to be injected into the engine, and wherein the desired first signal is indicative of an air-fuel equivalence ratio of greater than one.
13. An apparatus comprising: a processing circuit structured to: receive a key-on or key-off signal from an ignition circuit; provide a fuel cut or lean run signal to an engine; receive a lambda signal indicative of a downstream air-fuel equivalence ratio from a sensor positioned downstream of an intake of a catalyst; and provide a fault signal in response to the lambda signal indicating the downstream air-fuel equivalence ratio is less than one; and a notification circuit structured to

provide a notification indicating that the sensor is faulty in response to receiving the fault signal.

14. The apparatus of claim 13, wherein the fuel cut or lean run signal is structured to actuate the engine through at least one cycle with limited fuel so that the catalyst is flooded with oxygen.

15. The apparatus of claim 13, wherein the lambda signal is received after the key-on or key-off signal is received.

16. The apparatus of claim 13, wherein the lambda signal is received after the fuel cut or lean run signal is provided.

17. The apparatus of claim 13, wherein when the key-on signal is received, a time is recorded since the last key-off signal was received, and wherein the fault signal is only provided when the time exceeds a minimum absorption time.

18. The apparatus of claim 13, wherein the lambda signal indicating the downstream air-fuel equivalence ratio is less than one corresponds to the sensor being stuck rich.

19. The apparatus of claim 13, wherein when the key-off signal is received, the processing circuit provides the fuel cut signal to the engine.

20. The apparatus of claim 19, wherein the fuel cut signal causes the engine to operate in a fuel cut condition for a predetermined amount of time.
