(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
17 September 2015 (17.09.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/138342 A1

(51) International Patent Classification:
F02D 17/02 (2006.01) *F02P 5/04* (2006.01)
F02P 9/00 (2006.01)

(21) International Application Number:
PCT/US2015/019496

(22) International Filing Date:
9 March 2015 (09.03.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/952,737 13 March 2014 (13.03.2014) US

(71) Applicants: **TULA TECHNOLOGY, INC.** [US/US]; 2460 Zanker Road, San Jose, California 95131 (US). **GM GLOBAL TECHNOLOGY OPERATIONS LLC** [US/US]; 300 Renaissance Center, Detroit, Michigan 48265 (US).

(72) Inventors: **SHOST, Mark A.**; 16243 White Fir Court, Northville, MI 48168 (US). **SERRANO, Louis J.**; 260 Old Adobe Road, Los Gatos, California 95032 (US). **CARLSON, Steve E.**; 4227 Oakmore Road, Oakland, California 94602 (US). **SRINIVASAN, Vijay**; 29284 Wyndham Court, Farmington Hills, Michigan 48334 (US). **DEFENDERFER, Eric J.**; 6816 Wide Valley Drive, Brighton, Michigan 48116 (US). **WAGH, Nitish J.**; 39037 Cheshire Drive, Northville, Michigan 48167 (US). **BEIKMANN, Randall S.**; 841 Nelson Street, Brighton, Michigan 48116 (US). **LI, Jinbiao**; 3125 Baypoint Drive, Rochester Hills, Michigan 48309 (US).

(74) Agents: **YOON, Eric** et al.; Beyer Law Group LLP, P.O. Box 51887, Palo Alto, California 94303 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *with international search report (Art. 21(3))*

(54) Title: METHOD AND APPARATUS FOR DETERMINING OPTIMUM SKIP FIRE FIRING PROFILE

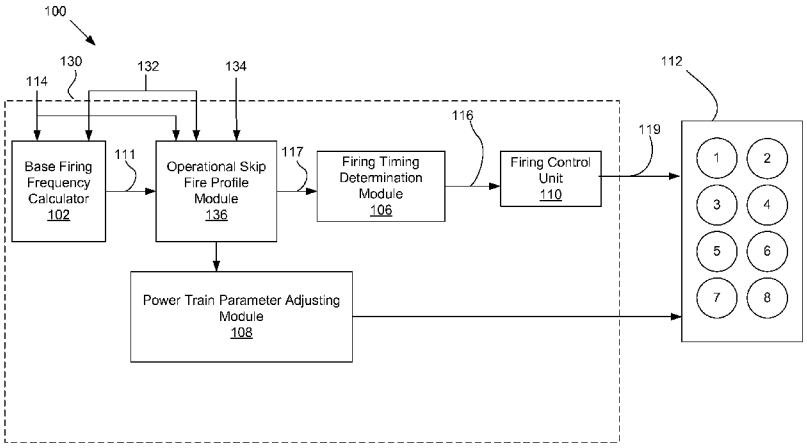


FIG. 4

(57) Abstract: In one aspect, a skip fire engine controller is described. The skip fire engine controller includes a skip fire module arranged to determine an operational firing fraction and associated cylinder load for delivering a desired engine output. The skip fire engine controller also includes a firing controller arranged to direct firings in a skip fire manner that delivers the selected operational firing fraction. Various methods, modules, lookup tables and arrangements related to the selection of a suitable operational firing fraction are also described.

WO 2015/138342 A1

METHOD AND APPARATUS FOR DETERMINING OPTIMUM SKIP FIRE FIRING PROFILE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/952,737, entitled "Method and Apparatus for Determining Optimum Skip Fire Firing Profile," filed March 13, 2014, which is incorporated herein in its entirety for all purposes.

FIELD OF THE INVENTION

[0002] The present invention relates to methods and systems for operating an engine in a skip fire manner. More specifically, different possible working chamber output levels are taken into account to help determine an optimal skip fire firing profile.

BACKGROUND

[0003] Most vehicles in operation today (and many other devices) are powered by internal combustion (IC) engines. Internal combustion engines typically have a plurality of cylinders or other working chambers where combustion occurs. Under normal driving conditions, the torque generated by an internal combustion engine needs to vary over a wide range in order to meet the operational demands of the driver. Over the years, a number of methods of controlling internal combustion engine torque have been proposed and utilized. Some such approaches contemplate varying the effective displacement of the engine. Engine control approaches that vary the effective displacement of an engine can be classified into two types of control, multiple fixed displacements and skip fire. In fixed multiple displacement control some fixed set of cylinders is deactivated under low load conditions; for example, an 8 cylinder engine that can operate on the same 4 cylinders under certain conditions. In contrast, skip fire control operates by sometimes skipping and sometimes firing any given cylinder. In general, skip fire engine control is understood to offer a number of potential advantages, including the potential of significantly improved fuel economy in many applications. Although the concept of skip fire engine control has been around for many years, and its benefits are understood, skip fire engine control has not yet achieved significant commercial success.

[0004] It is well understood that operating engines tend to be the source of significant noise and vibrations, which are often collectively referred to in the field as NVH (noise, vibration and harshness). In general, a stereotype associated with skip fire engine control is that skip fire operation of an engine will make the engine run significantly rougher, that is with increased NVH, relative to a conventionally operated engine. In many applications such as automotive applications, one of the most significant challenges presented by skip fire engine control is vibration control. Indeed, the inability to satisfactorily address NVH concerns is believed to be one of the primary obstacles that has prevented widespread adoption of skip fire types of engine control.

[0005] U.S. Patent Nos. 7,954,474; 7,886,715; 7,849,835; 7,577,511; 8,099,224; 8,131,445 and 8,131,447 and U.S. Patent Application Nos. 13/004,839; 13/004,844; and others, describe a variety of engine controllers that make it practical to operate a wide variety of internal combustion engines in a skip fire operational mode. Each of these patents and patent applications is incorporated herein by reference. Although the described controllers work well, there are continuing efforts to further improve the performance of these and other skip fire engine controllers to further mitigate NVH issues in engines operating under skip fire control. The present application describes additional skip fire control features and enhancements that can improve engine performance in a variety of applications.

SUMMARY

[0006] The present invention relates to methods and arrangements for operating an engine in a skip fire manner. In one aspect, a skip fire engine controller is described. The skip fire engine controller includes a skip fire profile module and a firing controller. The skip fire profile module is arranged to determine an operational firing fraction and associated cylinder load for delivering a desired engine output. The skip fire profile module is arranged to select the operational firing fraction from a set of available firing fractions. The set of available firing fractions varies as a function of cylinder load such that more firing fractions are available at lower cylinder loads than at higher cylinder loads. The firing controller is arranged to direct firings in a skip fire manner that delivers the selected operational firing fraction.

[0007] In another aspect, a skip fire engine controller is described. The skip fire engine controller includes a lookup table, a skip fire profile module and a firing controller. The lookup table is embodied in a computer readable media and includes table entries that indicate different maximum allowable cylinder loads at different engine speeds, transmission gears, and firing fractions. The skip fire profile module is arranged to determine an operational firing fraction suitable for delivering a requested engine output. The skip fire profile module utilizes the lookup table to determine the operational firing fraction. The firing controller is arranged to direct firings in a skip fire manner that delivers the operational firing fraction.

[0008] In still another aspect, a method for selecting an operational skip fire firing profile will be described. A desired engine output is determined. Multiple candidate firing fractions are selected from an allowed list of firing fractions. The candidate cylinder load for each of the candidate firing fractions is calculated such that the combination of the candidate cylinder load and each associated candidate firing fraction substantially yields the desired engine output. Each such combination is referred to as a candidate skip fire firing profile. One of the candidate skip fire firing profiles is selected as the operational skip fire firing profile. The internal combustion engine is operated based at least in part on the selected operational skip fire firing profile.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The invention and the advantages thereof, may best be understood by reference to the following description taken in conjunction with the accompanying drawings in which:

[0010] FIG. 1 is an exemplary plot of NVH versus engine speed for a selected firing frequency at various cylinder loadings and the resultant cylinder loading limit.

[0011] FIG. 2 is an exemplary plot of the cylinder load resulting in optimum fuel efficiency at different engine speeds.

[0012] FIG. 3 is an exemplary look up table compiling the base firing frequency for a range of engine torque fractions and engine speeds.

[0013] FIG. 4 is a block diagram illustrating an engine controller according to a particular embodiment of the present invention.

[0014] FIG. 5 is a flow diagram of a method for selecting an operational skip fire firing profile according to a particular embodiment of the present invention.

[0015] FIG. 6 is an exemplary two-dimensional look up table compiling the maximum acceptable cylinder load as a function of firing fraction and engine speed.

[0016] FIG. 7 is an exemplary one-dimensional look up table compiling acceptable engine speeds as a function of skip fire firing profiles.

[0017] FIG. 8 is an exemplary plot of NVH versus engine speed for a selected firing frequency at maximum cylinder load and the resultant cylinder loading limits associated with various acceptable NVH levels.

[0018] FIG. 9 is a flow diagram of a method for selecting an operational skip fire firing profile according to a particular embodiment of the present invention.

[0019] FIG. 10 is a graph indicating a relationship between specific fuel performance and cylinder load according to a particular embodiment of the present invention.

[0020] In the drawings, like reference numerals are sometimes used to designate like structural elements. It should also be appreciated that the depictions in the figures are diagrammatic and not to scale.

DETAILED DESCRIPTION

[0021] The present invention relates to a system for operating an internal combustion engine in a skip fire manner. More specifically, various implementations of the present invention take working chamber output into account to help determine a suitable skip fire firing frequency, firing fraction, firing pattern or firing sequence.

[0022] An internal combustion engine may be used as the power source for a motor vehicle. In vehicle applications, torque generated by the engine is transmitted to one or more of the vehicle's wheels. A power train, including a transmission having an adjustable gear ratio, is typically used to transmit the engine generated torque. Adjustment of the transmission alters the ratio between the engine rotation rate and the wheel rotation rate. During operation of a motor vehicle, a driver in the vehicle cabin typically demands a wide range of engine torque levels and engine speeds to accommodate varying driving conditions. Most vehicles in operation today operate all engine working chambers or cylinders at substantially equal load levels to accommodate these variable torque requests. That is the load on each cylinder in the engine is approximately constant, but the cylinder load goes up and down to meet the driver's torque request. For naturally aspirated spark-ignition engines, working chamber load level is adjusted primarily through use of throttling air flow into the engine. Operation in this manner is inefficient, since the working chambers are often operating far from maximum fuel efficiency conditions and throttling leads to pumping losses. Fuel efficiency can be significantly improved by operating the engine in a skip fire fashion where some working chambers are operating closer to optimum fuel efficiency and the remaining working chambers are deactivated.

[0023] In general, skip fire engine control contemplates selectively skipping the firing of certain cylinders during selected firing opportunities. Thus, for example, a particular cylinder may be fired during one firing opportunity and then may be skipped during the next firing opportunity and then selectively skipped or fired during the next. This is contrasted with conventional variable displacement engine operation in which a fixed set of the cylinders are deactivated during certain low-load operating conditions.

[0024] One challenge with skip fire engine control is reducing undesirable noise, vibration and harshness (NVH) to an acceptable level. The noise and vibration produced by the engine can be transmitted to occupants in the vehicle cabin through a variety of paths. Some of these paths, for example the drive train, can modify the amplitude of the

various frequency components present in the engine noise and vibration signature. Specifically, lower transmission gear ratios tend to amplify vibrations, since the transmission is increasing the torque and the torque variation at the wheels. The noise and vibration can also excite various vehicle resonances, which can then couple into the vehicle cabin.

[0025] Some noise and vibration frequencies can be particularly annoying for vehicle occupants. In particular, low frequency, repeating patterns (e.g., frequency components in the range of 0.2 to 8 Hz) tend to generate undesirable vibrations perceived by vehicle occupants. The higher order harmonics of these patterns can cause noise in the passenger cabin. In particular, a frequency around 40 Hz may resonate within the vehicle cabin, the so called "boom" frequency. Commercially viable skip fire engine control requires operating at an acceptable NVH level while simultaneously delivering the driver desired or requested engine torque output and achieving significant fuel efficiency gains.

[0026] The NVH characteristics vary with the engine speed, firing frequency, and transmission gear. For example, consider an engine controller that selects a particular firing frequency that indicates a percentage of firings necessary to deliver a desired torque at a particular engine speed and gear. Based on the firing frequency, the engine controller generates a repeating firing pattern to operate the working chambers of the engine in a skip fire manner. As is well known by those familiar in the art, at a given engine speed an engine that runs smoothly with some firing patterns may generate undesirable acoustic or vibration effects with other firing patterns. Likewise, a given firing pattern may provide acceptable NVH at one engine speed, but the same pattern may produce unacceptable NVH at other engine speeds. Engine induced noise and vibration is also affected by the cylinder load or working chamber output. If less air and fuel is delivered to a cylinder, the firing of the cylinder will generate less output, as well as less noise and vibration. As a result, if the cylinder output is reduced, some firing frequencies and sequences that were unusable due to their poor NVH characteristics may then become usable.

[0027] This concept is depicted graphically in FIG. 1, which shows an exemplary plot of NVH versus engine speed for a selected firing frequency and various cylinder loadings for a fixed transmission gear ratio. FIG. 1 shows a set of three curves, 151, 152 and 153, corresponding to different values of cylinder loading. Curve 151 corresponds to the maximum cylinder loading, while curves 152 and 153 correspond to successively lower

cylinder loading values. The cylinder loading may be defined by the cylinder torque fraction (CTF), which gives an indication of a working chamber output relative to a reference value. For example, the CTF values may be relative to the maximum possible output torque generated by a working chamber with wide open throttle at a reference ambient pressure and temperature, i.e. 100 kPa and 0 C, and the appropriate valve and sparking timing. Of course, other ranges and references values may be used. In this application CTF is generally a value between 0 and 1.0, although it may be greater than 1 in some circumstances, such as low ambient temperatures and/or operation below sea level or in boosted engines, i.e. engines with a supercharger or turbocharger. As shown in FIG. 1 lower levels of cylinder loading produce lower NVH, but the shape of the NVH curve is essentially constant for any fixed firing frequency and transmission gear ratio. In general, NVH is higher at low engine speeds because low engine speeds tend to generate vibration in the 0.2 to 8 Hz frequency range, which is particularly unpleasant to vehicle occupants. In addition, to high NVH at low engine speeds one or more resonances 150 in the NVH signature may be present at higher engine speeds. These peaks may correspond to the excitation of the cabin boom frequency or other resonances within the vehicle.

[0028] Also, shown in FIG. 1 is an acceptable NVH limit 160. This limit is shown as having a single, constant value for all engine speeds and driving conditions; however, as described below this need not be the case. In this example, the operating region below the NVH limit 160 represents a region of acceptable operating points from an NVH perspective, while regions above the NVH limit are excluded operating points. FIG. 1 also displays the cylinder load limit 171 as a function of engine speed. Curve 171 can be readily generated by comparing the NVH produced at each cylinder load and engine speed with the acceptable NVH limit. Inspection of the graph indicates that CTF values of 1, curve 151, are allowed at engine speeds above approximately 1000 rpm with the exception of the band around resonance 150 where engine speeds in the range of approximately 1950 to 2350 rpm are forbidden. For the lower CTF value of curve 152 operation is allowed at engine speeds above approximately 900 rpm with the exception of the band between approximately 2050 to 2250 rpm. For the lowest CTF shown, curve 153, operation is allowed at all engine speeds above approximately 700 rpm. Even though curve 153 displays the resonance 150, the maximum NVH at the resonant frequency is still below the allowable limit. In general, results similar to that shown in FIG. 1 may be

obtained for each firing frequency and transmission gear ratio. The curves may display multiple resonances at varying engine speeds having different NVH values, but all firing frequencies and transmission gear ratios will display qualitatively similar curves. Note that in a conventionally controlled engine, i.e. without skip fire, the family of curves obtained corresponds to the case of a firing frequency equal to 1.

[0029] The cylinder load can be varied by adjustment of various engine parameters, such as manifold absolute pressure (MAP), intake and exhaust valve timing, exhaust gas recirculation, and spark timing. The MAP is typically adjusted using a throttle to limit the size of the opening into the intake manifold. For engines with a cam shaft, the valve timing is adjusted using a cam phaser. Barometric pressure and ambient temperature also influence the cylinder load. For boosted engines the cylinder load may be varied by adjusting the boost level. In general, the cylinder load that provides for most efficient fuel utilization varies as a function of the engine speed. Highest fuel efficiency is typically obtained with the MAP at or near barometric pressure. The spark and cam phaser settings that yield highest fuel efficiency depend on the engine design. For each engine speed, the spark and cam phaser setting can be determined which yield the maximum fuel efficiency. The resultant optimum cylinder load that yields the highest fuel efficiency (CTF_{opt}) can be determined. FIG. 2 shows an exemplary graph of CTF_{opt} 180 versus engine speed. In general, at low engine speed CTF_{opt} is low, it increases and plateaus as the engine speed increases. At high engine speeds (not shown in FIG. 2) CTF_{opt} tends to decrease. Note that CTF_{opt} may vary depending on ambient conditions, such as the ambient temperature, humidity, and atmospheric pressure. Sensors located on the vehicle may detect these values and adjust CTF_{opt} based on the ambient conditions. The fuel quality, measured by octane rating or some comparable metric, may also influence the CTF_{opt} value.

[0030] The present application describes various engine controller implementations that take into account the above issues to provide fuel efficient operation with acceptable NVH characteristics. In some embodiments, for example, an engine controller uses a factor indicative of the engine or working chamber requested output (e.g., cylinder torque fraction, mass air charge (MAC), air per cylinder, brake torque, cylinder load, net mean effective pressure, or any other parameter related to engine or working chamber output) to help determine a firing frequency, firing fraction, pattern, sequence or other firing characteristic. Some implementations involve an engine controller that does not

determine a firing frequency based on the assumption that a particular fixed or maximum amount of air needs to be delivered to each fired cylinder. Instead, the engine controller considers the possibility of different air charge or working chamber output levels when determining a firing fraction or other firing characteristic. Generally, the engine controller is arranged to avoid or select particular firing frequencies, firing fractions, firing patterns or firing sequences, depending on current or anticipated operating parameters or engine settings.

[0031] An engine controller may use a lookup table, a control algorithm, or another mechanism that takes into account differing vehicle operating parameters or conditions when determining the acceptable NVH limit. The engine controller may use a lookup table to determine an appropriate firing fraction for operating the engine, given current and/or anticipated operating parameters. These and other embodiments will be described below with reference to the figures.

[0032] A general goal of any skip fire engine controller or skip fire engine control method is to deliver the requested engine output while minimizing fuel consumption and providing acceptable NVH performance. This is a challenging problem because of the wide range of operating conditions encountered during vehicle operation. A requested engine output may be expressed as a torque request at an engine operating speed. It should be appreciated that the amount of engine torque delivered can be represented by the product of the firing frequency and the cylinder load. Thus, if the firing frequency (FF) is increased, the cylinder load (CTF) can be decreased to generate the same engine torque, and vice versa. In other words,

$$\text{Engine Torque Fraction (ETF)} = \text{CTF} * \text{FF} \qquad \text{(Eq. 1)}$$

where the ETF is a value that represents normalized net or indicated engine torque. In this equation all values are dimensionless, which allows it to be used with all types of engines and in all types of vehicles. That is, to deliver the same engine torque, a variety of different firing frequencies and CTF combinations may be used. Equation 1 does not include the affects of engine friction. A similar analysis could be done including friction. In this case the calculated parameter would be brake torque fraction. Either engine net torque fraction, engine brake torque fraction, engine indicated torque fraction, or some

similar metric can be used as the basis of a control algorithm. For clarity the term engine torque fraction can refer to any of these measures of engine output and will be used in the subsequent discussion of engine controllers and engine control methods.

[0033] FIG. 3 shows an exemplary table 340 compiling the most fuel efficient operating firing frequency, denoted as a base firing frequency (FF_{base}), for a range of engine torque fractions (ETFs) and engine speeds. The firing frequency is defined as the ratio of cylinder firings relative to the firing opportunities, i.e. all cylinder operation. Each column 350 in FIG. 3 corresponds to an engine speed and each row 360 corresponds to an engine torque fraction. Each table entry 370 represents the base firing frequency, FF_{base}, which is the firing frequency that provides the most fuel efficient operation at the specified engine speed and torque request. The base firing frequency can readily be calculated using equation 1 in conjunction with knowledge of (CTF_{opt}) at different engine speeds (see FIG. 2). Two general trends are evident in base firing frequency behavior. First, for fixed engine speed as the engine torque request increases the base firing frequency increases to match the required load. Secondly, for a fixed ETF as the engine speed increases the base firing frequency decreases. This reflects the fact shown in FIG. 2 that the cylinder loading which provides optimum fuel efficiency tends to increase as the engine speed increases. These trends will generally be present in all internal combustion engines; however, the exact values of the base firing frequency will vary depending on details of the engine design. Entries without a value cannot deliver the requested torque at (CTF_{opt}), since the firing frequency cannot be greater than 1. In order to deliver these torque levels, the cylinders will need to be operated with CTF values greater than CTF_{opt}. However, even in these situations skip fire operation is generally more efficient than conventional engine control, since skip fire operation allows the cylinder load to more closely match CTF_{opt}. While it is generally advantageous for the FF_{base} values in Figure 3 to represent the most fuel efficient firing fraction to deliver the request engine torque, other criteria may be used to define FF_{base}.

[0034] Referring to FIG. 4, an engine 100 according to a particular embodiment of the present invention will be described. The engine 100 consists of an engine controller 130 and the working chambers of the engine 112. The engine controller 130 receives an input signal 114 representative of the desired engine output and various vehicle operating parameters, such as an engine speed 132 and transmission gear 134. The input signal 114

may be treated as a request for a desired engine output or torque. The signal 114 may be received or derived from an accelerator pedal position sensor (APP) or other suitable sources, such as a cruise controller, a torque calculator, etc. An optional preprocessor may modify the accelerator pedal signal prior to delivery to the engine controller 130. However, it should be appreciated that in other implementations, the accelerator pedal position sensor may communicate directly with the engine controller 130. The engine controller 130 may include a base firing frequency calculator 102, an operational skip fire profile module 136, a power train parameter adjustment module 108, a firing timing determination module 106, and a firing control unit 110. The engine controller 130 is arranged to operate working chambers of the engine 112 in a skip fire manner.

[0035] The base firing frequency calculator 102 receives input signal 114 (and when present other suitable sources) and engine speed 132 and is arranged to determine a base firing frequency 111 that would be appropriate to deliver the desired output. The base firing frequency 111 is the firing frequency that delivers the requested torque at the most fuel efficient firing frequency and cylinder load as described relative to FIG. 3.

[0036] The base firing frequency 111 is input into the operational skip fire profile module 136. The operational skip fire profile is determined based at least in part on the engine speed 132 and transmission gear 134, which are both inputs to the operational skip fire profile module 136. The input signal 114 may also serve as an input to the operational skip fire profile module 136. The operational skip fire profile module 136 determines an operational skip fire profile. The operational skip fire profile includes both an operational firing fraction (FF_{op}) and a factor indicative of working chamber output, such as cylinder torque fraction, CTF. Other indicators of cylinder load may be used in place of cylinder torque fraction, such as brake torque, cylinder load, net mean effective pressure, air per cylinder (APC), mass air charge (MAC) or any other parameter that is related to working chamber output. In various embodiments, the determination of the operational skip fire profile is based on various operating parameters, including but not limited to engine speed, transmission gear, road conditions, driver settings, accelerator pedal position and the rate of change of the accelerator pedal position

[0037] The operational skip fire profile module 136 takes into account multiple possible working chamber output levels when determining a suitable firing fraction. There are a wide variety of ways in which the operational skip fire profile module 136 can take

into account different possible working chamber output levels. In some embodiments, for example, the operational skip fire profile module 136 references one or more lookup tables. The lookup tables may contain entries that indicate allowable engine speeds, cylinder loads and/or other engine parameters for particular firing fractions or frequencies (e.g, as illustrated in FIGS. 6 and 7.) One or more possible skip fire firing profiles are evaluated using the lookup tables. Each skip fire firing profile produces a desired engine torque via some combination of firing frequency and cylinder torque fraction. Some of these skip fire firing profiles will produce unacceptable NVH over certain engine speed ranges and gear settings and will be excluded from consideration as the operational skip fire profile. Among the remaining skip fire profiles the operational skip fire module 136 may advantageously select the skip fire profile having the best fuel efficiency as the operational skip fire profile. Alternatively the operational skip fire module 136 may use alternative criteria for making the determination of the operational skip fire profile.

[0038] In the illustrated embodiment shown in FIG. 4, a power train parameter adjusting module 108 is provided that cooperates with the operational skip fire profile module 136. The power train parameter adjusting module 108 directs the engine working chambers 112 to set selected power train parameters appropriately to ensure that the actual engine output substantially equals the requested engine output at the operational firing fraction. For example, if the operational skip fire profile module 136 determines that a higher firing fraction may be used, but would require the use of a lower working chamber output level or air charge, the power train parameter adjusting module would help ensure that a suitable, lower amount of air is delivered to the fired working chambers. The power train parameter adjusting module 108 may be responsible for setting any suitable engine setting (e.g., mass air charge, spark timing, cam timing, valve control, exhaust gas recirculation, throttle, etc.) to help ensure that the actual engine output matches the requested engine output.

[0039] The firing timing determination module 106 receives the operational firing fraction 117 from the operational skip fire profile module 136 and is arranged to issue a sequence of firing commands that cause the engine to deliver the percentage of firings dictated by an operational firing fraction 117. The sequence of firing commands (sometimes referred to as a drive pulse signal 116) outputted by the firing timing

determining module 106 are passed to the firing control unit 110 which orchestrates the actual firings through firing signals 119 directed to the engine working chambers 112.

[0040] It should be appreciated that the engine controller 130 is not limited to the specific arrangement shown in FIG. 4. One or more of the illustrated modules may be integrated together. Alternatively, the features of a particular module may instead be distributed among multiple modules. The engine controller may also include additional features, modules or operations based on other patent applications, including U.S. Patent Nos. 7,954,474; 7,886,715; 7,849,835; 7,577,511; 8,099,224; 8,131,445; 8,131,447; and 8,616,181; U.S. Patent Application Nos. 13/774,134; 13/963,686; 13/953,615; 13/953,615; 13/886,107; 13/963,759; 13/963,819; 13/961,701; 13/963,744; 13/843,567; 13/794,157; 13/842,234; 13/654,244, 13/654,248 and 13/654,244 and; and U.S. Provisional Patent Application Nos. 61/080,192; 61/104,222; and 61/640,646, each of which is incorporated herein by reference in its entirety for all purposes. Any of the features, modules and operations described in the above patent documents may be added to the illustrated engine controller 130. In various alternative implementations, these functional blocks may be accomplished algorithmically using a microprocessor, ECU or other computation device, using analog or digital components, using programmable logic, using combinations of the foregoing and/or in any other suitable manner.

[0041] Referring next to FIG. 5, a method for determining an operational skip fire profile 200 according to a particular embodiment of the present invention will be described. The operational skip fire profile consists of an operational firing fraction and cylinder torque fraction or some equivalent measure of cylinder output. In various embodiments, the operational skip fire profile module 136 and/or the engine controller 130 perform the steps of FIG. 5.

[0042] At step 202, a torque request is determined based on input signal 114 (from FIG. 4) and the current engine operating speed. The input signal 114 is derived from any suitable sensor(s) or operating parameter(s), including, for example, an accelerator pedal position sensor.

[0043] At step 204, the base firing frequency calculator 102 determines a base firing frequency and base cylinder torque fraction. The base firing frequency and base cylinder torque fraction is the combination that yields the optimum fuel efficiency while delivering the requested torque. The operational skip fire profile module 136 then selects a candidate

firing fraction from a set of available firing fractions (step 206). The candidate firing fraction may be the firing fraction closest to the base firing frequency. The operational skip fire profile module 136 then determines a candidate cylinder torque fraction from the torque request and candidate firing fraction using Eq. 1 (step 208).

[0044] The operational skip fire profile module 136 then interrogates a firing profile table to determine whether the candidate firing fraction and cylinder torque fraction are allowed (step 210). Inputs to this decision are the current engine speed and transmission gear (step 209). If the candidate torque fraction is allowed for this candidate firing fraction the process moves to step 212 where the candidate firing fraction and candidate cylinder torque request are selected as the operating firing fraction and operating cylinder torque fraction, i.e. the operational skip fire firing profile. The process then moves to step 214 where the engine is operated using the operational skip fire firing profile.

[0045] If in step 210 it is determined that the candidate cylinder torque fraction is unacceptable, the process proceeds to step 211 where a new candidate firing fraction is selected. The process then proceeds again to step 208 where the cylinder torque fraction associated with the new candidate firing fraction is calculated. A determination is then made if this new skip firing profile is acceptable (step 210). This loop proceeds until an acceptable candidate firing fraction is selected. Once this occurs the process proceeds through steps 212 and 214 as previously described.

[0046] A lookup table may be used in step 210 of FIG. 5 to determine whether the candidate cylinder torque fraction for the candidate firing fraction is allowed. FIG. 6 is a sample lookup table 300. Each row in the lookup table 300 corresponds to a particular firing fraction or firing frequency. In this example, each row indicates a maximum allowed cylinder torque fraction for a corresponding firing fraction. For any given firing fraction, the maximum allowed CTF may differ based on engine speed and/or other parameters. The rows may be arranged in ascending order from the lowest operating firing fraction, 1/9, to the highest firing fraction, 1. In table 300 all firing fractions with denominators of 9 or less are allowed. It should be appreciated that is some cases lower and higher maximum values for the firing fraction denominator may be used. Associated with each row is a maximum CTF value associated with each engine operating speed. . In some cases it may be possible to provide a single CTF limit for each firing fraction without reference to the engine speed.

[0047] As an aid in understanding use of the look up table 300 shown in FIG. 6, consider a specific example of a torque request of 0.10 and an engine speed of 1000 rpm (this corresponds to the entry 370 in FIG. 3). From FIG. 3 the base firing frequency is 0.211. Interrogation of the lookup table 300 shows that the closest firing fraction to the base firing frequency is 1/5 or 0.200. This is selected as the candidate firing fraction (step 206). From equation 1 the required cylinder torque fraction may be determined as 0.1/0.200 or 0.5. The look up table 300 may then be interrogated to determine if a CTF of 0.5 is acceptable. In this case the value in the CTF limit table 372 is 0.06, so a CTF of 0.5 is unacceptable and a new candidate firing fraction must be selected as indicated in step 211. This may be done in multiple ways. One method is to increase the candidate firing fraction to the adjacent higher value, equivalent to stepping down a row in table 300, and repeating the process. In this case, the new candidate firing fraction would be 2/9 and the corresponding candidate CTF would be 0.1/(2/9) or 0.45 (step 208). Interrogation of table 300 (step 210) indicates that the appropriate maximum CTF value 373 is 0.03, so the candidate cylinder torque fraction of 0.45 is again unacceptable. The candidate firing fraction may again be incremented (step 211) and the new firing fraction is 1/3. The corresponding candidate CTF is 0.1/(1/3) or 0.3. Interrogation of table 300 (step 210) indicates that the appropriate maximum CTF value 374 is 0.51, so the candidate cylinder torque fraction of 0.3 is acceptable. The candidate firing fraction and cylinder torque fraction can then be selected as the operating firing fraction and cylinder torque fraction (step 212). The engine may be operated with this firing fraction and cylinder torque fraction (step 214).

[0048] Other search methods may be used in table 300 to determine an acceptable skip fire firing profile. For example, instead of incrementing the firing fraction to the next higher allowed firing fraction if the candidate firing fraction is unacceptable, the algorithm could move to the next closest firing fraction to the base firing frequency. This may be a smaller firing fraction than the original candidate firing fraction. Also, instead of choosing the firing fraction closest to the base firing frequency as the initial candidate firing fraction, the algorithm could select the closest firing fraction having a value greater than the base firing frequency. The search for an acceptable skip fire firing profile need not start with selecting the candidate firing fraction closest to the base firing frequency.

Other search methods may be used with the goal of finding an acceptable skip fire firing profile with operating conditions at or near those that give rise to optimal fuel efficiency.

[0049] In general, acceptable skip fire firing profiles will be found by moving to higher firing fractions, since the associated cylinder torque fraction will be lower. In the extreme case the firing fraction moves to 1 and the engine operates on all cylinders, just as a conventionally controlled engine. An important advantage of various implementations of the present invention is the ability to operate the engine at an acceptable NVH at firing fractions at or close to the base firing frequency, which results in improved fuel economy.

[0050] An advantage of various embodiments of the present invention is that they take into account cylinder load and fuel efficiency in determining an acceptable firing fraction. That is, they do not necessarily assume that firing cylinders need to be operated at or near their optimal efficiency. In some cases an undesirable frequency can still be acceptable, if its amplitude is sufficiently low. Various embodiments recognize when operating at reduced cylinder loads the NVH is lower than operating at the cylinder load corresponding to optimum fuel efficiency. This allows access to firing fractions that are closer to the base firing frequency and thus yields improved fuel efficiency.

[0051] There are a variety of methods that the information displayed in table 300 (FIG. 6) may be presented and interrogated. Table 300 is a two-dimensional table with the entries corresponding to the maximum allowed CTF at any given firing fraction and engine speed for a given transmission gear. The information can alternatively be expressed as a one-dimensional table where each row of the table lists a firing fraction and maximum CTF. This means that the list of data encompassing the maximum CTF and ranges of engine speed operation can be considered to be a single entry for purposes of this description. Associated with each entry are acceptable engine operating speeds. Different tables may be constructed for each transmission gear ratio. It should be appreciated for a vehicle with a continuously variable transmission, i.e. not having fixed gear ratios, the tables can be constructed for different ranges of transmission speed ratios. FIG. 7 shows a portion of such a table 700. Each row 740 corresponds to a firing fraction and maximum allowed cylinder torque fraction. The rows may be arranged first based on firing fraction and then on cylinder torque fraction as shown in FIG. 7, although other arrangements also may be used. Each row indicates the allowable engine operation speeds

associated with a particular maximum allowed CTF and a firing fraction. In table 700 the acceptable engine speeds are depicted by a series of allowed ranges. For the values shown in table 700 up to three ranges are used, although more ranges and fewer ranges may be used in some cases. Alternatively, other methods of representing the allowed engine speeds may be shown. Generally as the CTF level decreases the allowable range of engine speeds increases, since the energy associated with each firing is reduced. Conversely, the allowed speed range narrows as the CTF is increased for a fixed firing fraction. This is consistent with the physical model shown in FIG. 1. In table 700 some engine speed range is acceptable for all listed firing fractions; however, in some situations a firing fraction may have no allowed engine speeds. For example, some firing fractions may be excluded when operating in a certain transmission gear.

[0052] The selection of an operational skip fire firing profile and/or corresponding firing fraction may be performed in a wide variety of ways. In various implementations, for example, a linear search or algorithm is used to navigate a lookup table to determine a suitable profile. In the lookup table 700 of FIG. 7, for example, the following algorithm may be used to find a suitable skip fire firing profile/firing fraction:

1) Start in the top row of the table.

2) Move to the next row until the firing fraction is larger than the base firing frequency.

3) In that row, look at the CTF limit column. If the value in the CTF limit column is smaller than the candidate CTF, go to step 4. Otherwise, repeat step 2.

4) If the current engine speed is outside of the allowed operating ranges in table 700, move to the next row and repeat step 3. Otherwise, stop here. The candidate firing fraction and corresponding cylinder torque fraction yield acceptable NVH performance while maximizing fuel efficiency. These conditions represent the operational skip fire firing profile. Note that under any condition, the row corresponding to a firing fraction of 1 is acceptable, so the search always ends successfully.

[0053] In various embodiments, the rows of the table are analyzed in the order of low-to-high firing fractions. That is, if the current operating conditions do not provide acceptable NVH performance, the operational skip fire profile module 136 then moves on to the row for the next highest firing fraction. A determination is again made as to whether the current operating parameters meet the acceptable NVH criteria, and the

process continues until a suitable firing fraction is found and/or all the available profiles have been considered, which would revert engine operation to a firing fraction of 1. As a result, in some implementations, operational skip fire profile module 136 selects the operational skip fire firing profile with the lowest firing fraction that meets the following criteria: 1) the profile is suitable for delivering the desired torque; and 2) the current or anticipated operating parameters provide acceptable NVH performance for the selected firing fraction.

[0054] Once operational skip fire profile module 136 has selected a suitable operational skip fire firing profile, the firing timing determination module 106 (from FIG. 4) generates a firing sequence based on the selected profile (step 210 of FIG. 5). In some embodiments, for example, each profile corresponds to an available firing fraction. This operational firing fraction 117 is then received by the firing timing determination module 106. The firing timing determination module generates a firing sequence 116, which is sent to the firing control unit 110 based on the operational firing fraction 117. The firing control unit 110 in turn directs the working chambers of the engine 112 to operate in a skip fire manner based on the firing sequence 119.

[0055] In addition to presenting the acceptable skip fire firing profiles in a one-dimensional table like table 700 and a two-dimensional table like table 300, the acceptable profiles may also be compiled in a three dimensional table that lists engine speed, transmission gear, and firing fraction as the variables and maximum CTF as the table entry. This table contains information on which cylinder loads are allowed for each firing fraction, transmission gear setting, and engine speed. Similar tables can be constructed using different variables, but can provide substantially the same information, i.e. acceptable skip fire firing profiles for different vehicle operating conditions.

[0056] It should be appreciated that the lookup tables in the figures are only for illustrative purposes and that the concept of determining acceptable skip fire firing profiles may be implemented in a wide variety of ways. The format and structure of the data, the number of entries, the inputs to the lookup table, the number of lookup tables and the values in the lookup table can, of course, be modified to suit the needs of different applications. Generally, the data from the aforementioned tables can be stored in or involve any suitable mechanism, data structure, software, hardware, algorithm or lookup

table that indicates or represents usage constraints for particular types of firing-related operations, characteristics or firing fractions.

[0057] In particular in some embodiments an operational skip fire profile may be determined without first determining a base firing frequency. In this case, a number of candidate skip fire profiles may be considered by the operational skip fire profile module 136 that deliver the requested torque. The operational skip fire profile module 136 may then select from these candidate skip fire profiles based on multiple criteria; including, but not limited to, NVH and fuel efficiency.

[0058] In additional embodiments of the present invention multiple levels of acceptable NVH may be used. Selection of the appropriate NVH level may depend on many conditions such as a vehicle operating parameter, road roughness, cabin noise level, and/or user preference. FIG. 8 graphically depicts this embodiment. FIG. 8 is similar to FIG. 1 with the horizontal axis being engine speed, the left vertical axis being NVH level and the right vertical axis being the maximum acceptable cylinder load. As in FIG. 1 curve 151 corresponds to the maximum cylinder loading, i.e. CTF=1. Curve 151 has a resonance 150 at an engine speed of approximately 2200 rpm. In this case there are three different acceptable levels of NVH corresponding to curves 160, 161, and 162. Curve 161 corresponds to the most restrictive NVH criteria. Curve 162 corresponds to the least restrictive NVH criteria. Curve 160 corresponds to intermediate NVH criteria. Associated with the different acceptable NVH levels are the corresponding maximum cylinder loading limits. For the least restrictive NVH criteria, curve 162, the resulting maximum cylinder load curve is 172. In this case the engine is allowed to operate at maximum cylinder load for all engine speeds, except low speeds below approximately 750 rpm. For the most restrictive NVH criteria, curve 161, the corresponding maximum cylinder load curve is 171. In this case there are two ranges of engine speeds where operation at maximum CTF is allowed. The first range is between approximately 1150 and 1750 rpm and the second range is above 2500 rpm. At the intermediate NVH level of curve 160, the resulting maximum cylinder load limit curve is 170. This is the same case described in relation to FIG. 1. While FIG. 8 shows the acceptable NVH level in all cases to be independent of engine speed, this is not necessarily the case. For example, higher NVH levels may be acceptable at high engine speeds.

[0059] Referring next to FIG. 9, a method 500 for determining a skip fire firing profile according to the embodiment discussed relative to FIG. 8 will be described. The method 500 involves using one or more operating parameters to determine what constitutes an acceptable NVH level. This level can vary depending on the operating parameters, and thus the acceptable skip fire firing profiles may also vary.

[0060] In some situations, it is desirable to use more or less restrictive NVH criteria. The degree of restrictiveness may depend on the rate and direction of the accelerator pedal position change. Less restrictive NVH criteria may be applied when the pedal is tipped in and more restrictive criteria applied when the pedal is tipped out. Aggressive tip in indicates that the driver is rapidly demanding increasing torque from the engine and under these conditions acceptable NVH criteria may be relaxed. The degree of restrictiveness may also depend on or be affected by a wide variety of detected conditions e.g., when a shift between gears is detected, vehicle speed, road conditions, or when it is determined that the engine is in idle. Additionally, the criteria may depend on factors other than those associated with the engine power train, such as the roughness of the road or noise level in the vehicle cabin. In some cases the level of acceptable NVH may be selectable by the vehicle driver. The driver may make a tradeoff between the acceptable NVH level and fuel economy.

[0061] The illustrated method 500 provides one example implementation of the above approach. The illustrated method is similar to that described in relation to FIG. 5, with the exception of adding an operating parameter input that causes different look up tables or control algorithms to be used to determine acceptable skip fire firing profiles.

[0062] Inputs to the method 500 include a driver torque request or equivalent 551, an engine speed 552, a transmission gear 553, and a vehicle or user determined operating parameter 554.

[0063] At step 502, a torque request is determined based on torque request 551 and the current engine operating speed 552.

[0064] At step 504, a base firing frequency and base cylinder torque fraction are determined. The base firing frequency and base cylinder torque fraction is the combination that yields the optimum fuel efficiency while delivering the requested torque.

[0065] At step 506, a candidate firing fraction is selected from a set of available firing fractions. The available firing fractions may depend on the transmission gear setting 553

and the vehicle operating parameter 554. The vehicle operating parameter 554 may be any parameter that helps determine whether less or more restrictive NVH criteria should be used (e.g., the rate and direction of accelerator pedal position change, etc.)

[0066] At step 508 a candidate cylinder torque fraction is determined that would result in the engine producing the desired torque at the candidate firing fraction. The operational skip fire profile module 136 (Fig. 4) then determines a candidate cylinder torque fraction from the torque request and candidate firing fraction using Eq. 1. At step 510 a firing profile table is interrogated to determine whether the candidate firing fraction and cylinder torque fraction are allowed. The values (e.g., maximum CTF values, etc.) in the table, whose format and usage may resemble table 300 of FIG. 6 and table 700 of FIG. 7, may differ depending on the operating parameter 554. Inputs to the determination at step 510 are the current engine speed 552, transmission gear 553, and vehicle parameter 554. If the candidate torque fraction is allowed, the process moves to step 512 where the candidate firing fraction and candidate cylinder torque request are selected as the operating firing fraction and operating cylinder torque fraction, i.e. the operational skip fire firing profile. The process then moves to step 514 where the engine is operated using the operational skip fire firing profile.

[0067] If in step 510 it is determined that the candidate cylinder torque profile is unacceptable, the process proceeds to step 511 where a new candidate firing fraction is selected. The process then proceeds again to step 508 where the cylinder torque fraction associated with the new candidate firing fraction is calculated. A determination is then made if this new skip firing profile is acceptable (step 510). This loop proceeds until an acceptable candidate firing fraction is selected. Once this occurs the process proceeds through steps 512 and 514 as previously described.

[0068] Referring next to FIG. 10, a graph 1000 indicating a relationship between cylinder load and fuel consumption according to a particular embodiment of the present invention will be described. The vertical axis for the graph 1000 corresponds to specific fuel consumption. The lower the specific fuel consumption, the greater the fuel efficiency. The horizontal axis for the graph 1000 corresponds to cylinder load. The optimally fuel efficient CTF level is indicated by a point on the curve 1002 that is labeled as CTF_{opt}. The curve 1002 assumes a particular engine speed and may vary as the engine

speed changes. Other factors such as fuel quality, atmospheric pressure, ambient temperature and other external factors may influence curve 1002.

[0069] Some implementations of the present invention involve storing data indicated by the graph 1000 in a data structure at an engine controller 130. This cylinder load/fuel consumption data may be stored in any suitable data structure, including but not limited to a lookup table. The cylinder load/fuel consumption data may be provided for a wide range of engine speeds. The cylinder load/fuel consumption data helps indicate fuel usage or efficiency, given a particular engine speed, cylinder load and/or other engine parameter. The engine controller 130 may use the information on fuel efficiency stored in the look up table to determine the most fuel efficient operational skip fire firing profile.

[0070] The data may be used in a wide variety of ways. In some embodiments, for example, multiple candidate firing fractions are selected. A candidate cylinder load is calculated for each of the candidate firing fractions such that each cylinder load-firing fraction combination delivers a desired engine output. The aforementioned cylinder load/fuel consumption data is then used to determine which of these combinations is the most fuel efficient. The most fuel efficient combination or skip fire firing profile is then used in operating the engine. In some embodiments, for example, the firing fraction selected in this manner is used as the base firing fraction, as described in step 204 of FIG. 5.

[0071] Any and all of the described components may be arranged to refresh their determinations / calculations very rapidly. In some preferred embodiments, these determinations / calculations are refreshed on a firing opportunity by firing opportunity basis although, that is not a requirement. In some embodiments, for example, the selection of an operational skip fire firing profile (e.g., step 212 of FIG. 5 or step 512 of FIG. 9) is performed on a firing opportunity by firing opportunity basis. An advantage of firing opportunity by firing opportunity control of the various components is that it makes the engine very responsive to changed inputs and/or conditions. Although firing opportunity by firing opportunity operation is very effective, it should be appreciated that the various components can be refreshed more slowly while still providing good control (e.g., the firing fraction determinations may be performed every revolution of the crankshaft, every two or more firing opportunities, etc.).

[0072] Aside from NVH considerations other considerations may influence the choice of an acceptable operational skip fire firing profile. For example, in some cases it may be desirable to decrease the intake manifold pressure for a period of time to supply vacuum for various vehicle components, such as the power brakes. In this case operation at the skip fire firing profile which provides for optimum fuel efficiency would be prohibited, since it would not draw significant manifold vacuum. Different look up tables or a different search algorithm could be used to determine the skip fire firing profile which satisfies this intake manifold pressure constraint while simultaneously maximizing fuel economy. Similarly in the event of persistent engine knocking or malfunction of a given cylinder, different skip fire firing profiles may be used which substantially eliminate the engine knocking or avoid use of the malfunctioning cylinder.

[0073] It should be appreciated that the allowable firing fractions listed in table 600 and table 700 may be different for different gears, vehicle parameters, and driving conditions. For example less restrictive NVH constraints may allow more firing fractions than more restrictive NVH constraints. Also, not all combinations of numerator and denominator need to be included in a table. For example, in some situations 1/9 may be the only allowed firing fraction with a denominator of 9. Judicious choice of the allowable firing fractions may result in a more uniform distribution of allowed firing fraction.

[0074] The invention has been described primarily in the context of operating a naturally aspirated, 4-stroke, internal combustion piston engines suitable for use in motor vehicles. However, it should be appreciated that the described applications are very well suited for use in a wide variety of internal combustion engines. These include engines for virtually any type of vehicle – including cars, trucks, boats, aircraft, motorcycles, scooters, etc.; and virtually any other application that involves the firing of working chambers and utilizes an internal combustion engine. The various described approaches work with engines that operate under a wide variety of different thermodynamic cycles – including virtually any type of two stroke piston engines, diesel engines, Otto cycle engines, Dual cycle engines, Miller cycle engines, Atkinson cycle engines, Wankel engines and other types of rotary engines, mixed cycle engines (such as dual Otto and diesel engines), hybrid engines, radial engines, etc. It is also believed that the described approaches will work well with newly developed internal combustion engines regardless of whether they operate utilizing currently known, or later developed thermodynamic cycles. Boosted

engines, such as those using a supercharger or turbocharger may also be used. In this case the maximum cylinder load may correspond to the maximum cylinder air charge obtained by boosting the air intake.

[0075] It should be also appreciated that any of the operations described herein may be stored in a suitable computer readable medium in the form of executable computer code. The operations are carried out when a processor executes the computer code. Such operations include but are not limited to any and all operations performed by the firing fraction calculator 102, the firing timing determination module 106, the firing control unit 110, the power train parameter adjusting module 108, operational skip fire profile module 136, the engine controller 130, or any other module, component or controller described in this application.

[0076] Although only a few embodiments of the invention have been described in detail, it should be appreciated that the invention may be implemented in many other forms without departing from the spirit or scope of the invention. There are several references to the term, firing fraction. It should be appreciated that a firing fraction may be conveyed or represented in a wide variety of ways. For example, the firing fraction may take the form of a firing pattern, sequence or any other firing characteristic that involves or inherently conveys the aforementioned percentage of firings. There are also several references to the term, "cylinder." It should be understood that the term cylinder should be understood as broadly encompassing any suitable type of working chamber. Therefore, the present embodiments should be considered illustrative and not restrictive and the invention is not to be limited to the details given herein.

CLAIMS

What is claimed is:

1. A skip fire engine controller comprising:

a skip fire profile module arranged to determine an operational firing fraction and associated cylinder load for delivering a desired engine output, wherein the skip fire profile module is arranged to select the operational firing fraction from a set of available firing fractions, wherein the set of available firing fractions varies as a function of cylinder load such that more firing fractions are available at lower cylinder loads than at higher cylinder loads; and

a firing controller arranged to direct firings in a skip fire manner that delivers the selected operational firing fraction.

2. A skip fire engine controller as recited in claim 1 wherein:

the selection of the operational firing faction is based in part on determining which of the set of available firing fractions is more fuel efficient.

3. A skip fire engine controller as recited in claim 1 or 2 wherein:

the selection of the operational firing fraction involves using a lookup table that indicates different maximum allowable cylinder loads at different engine speeds and firing fractions.

4. A skip fire engine controller as recited in any of claims 1-3 wherein:

each of the available firing fractions is associated with a maximum allowable cylinder load;

at least some of the available firing fractions are associated with different maximum allowable cylinder loads; and

the selection of the operational firing fraction is based at least in part on the maximum allowable cylinder load for at least some of the available firing fractions.

5. A skip fire engine controller as recited in claim 4, the skip fire profile module being further arranged to:

calculate a cylinder load necessary to deliver the desired engine output; and

determine whether the calculated cylinder load exceeds the maximum allowable cylinder load associated with one of the available firing fractions.

6. A skip fire engine controller as recited in any of claims 1-5 wherein the selection of the operational firing fraction is based at least in part on one selected from the group consisting of operating gear, road conditions, gear shift, vehicle speed, cabin noise level, presence of engine idle, accelerator pedal position and rate of change in a position of an accelerator pedal.

7. A skip fire engine controller as recited in any of claims 1-6 wherein the selection of the operational firing fraction is performed on a firing opportunity by firing opportunity basis.

8. A skip fire engine controller as recited in any of claims 1-7 wherein the selection of the operational firing fraction is performed at least once every engine cycle.

9. A skip fire engine controller comprising:

a lookup table embodied in a computer readable media, the lookup table including table entries that indicate different maximum allowable cylinder loads at different vehicle operating parameters;

a skip fire profile module arranged to determine an operational firing fraction suitable for delivering a requested engine output, wherein the skip fire profile module utilizes the lookup table to determine the operational firing fraction; and

a firing controller arranged to direct firings in a skip fire manner that delivers the operational firing fraction.

10. A skip fire engine controller as recited in claim 9 wherein:

the lookup table includes one or more indices, each index being selected from the group consisting of engine speed, transmission gear, and firing fraction.

11. A skip fire engine controller as recited in claim 9 or 10 wherein:

the firing fraction determination is based at least in part on a base firing fraction;

the skip fire engine controller further comprises a base firing fraction calculator that indicates a base firing fraction that is substantially optimally fuel efficient for a given engine speed and engine output.

12. A skip fire engine controller as recited in claim 11 wherein:

the lookup table includes a set of available firing fractions; and

the skip fire profile module is further arranged to select a candidate firing fraction from the set of available firing fractions in the lookup table wherein the candidate firing fraction is a firing fraction in the lookup table that is closer to the base firing fraction than

other firing fractions in the lookup table.

13. A skip fire engine controller as recited in claim 11 or 12 wherein:

the candidate firing fraction is associated with a maximum allowed cylinder load in the lookup table; and

the skip fire profile module is further arranged to:

determine a candidate cylinder load that, together with the candidate firing fraction, is able to deliver the requested engine output; and

determine whether the candidate cylinder load exceeds the maximum allowed cylinder load.

14. A skip fire engine controller as recited in any of claims 9-13 wherein:

at least some values in the lookup table are different based on at least one selected from the group consisting of road conditions, gear shift, vehicle speed, cabin noise level, presence of engine idle, accelerator pedal position and rate of change in a position of an accelerator pedal.

15. A skip fire engine controller as recited in any of claims 9-14 wherein:

the lookup table is one dimensional; and

each table entry indicates a maximum allowed cylinder load for a vehicle parameter, each parameter being selected from the group consisting of engine speed, transmission gear, and firing fraction.

16. A skip fire engine controller as recited in any of claims 9-15 wherein:

the lookup table is two dimensional; and

each table entry indicates a maximum allowed cylinder load for a set of two vehicle parameters, each of the two parameters being selected from the group consisting of engine speed, transmission gear, and firing fraction.

17. A skip fire engine controller as recited in any of claims 9-16 wherein:

the lookup table is three dimensional; and

each table entry indicates a maximum allowed cylinder load for a firing fraction, a range of engine speeds and a transmission gear.

18. A method of selecting an operational skip fire firing profile suitable for use in operating an internal combustion engine in a skip fire manner to produce a desired engine output, the method comprising:

determining a desired engine output;

selecting a plurality of candidate firing fractions from an allowed list of firing fractions;

calculating a candidate cylinder load for each of the plurality of candidate firing fractions such that the combination of the candidate cylinder load and each associated candidate firing fraction substantially yields the desired engine output, each such combination being a candidate skip fire firing profile;

selecting one of the candidate skip fire firing profiles as the operational skip fire firing profile; and

operating the internal combustion engine based at least in part on the operational skip fire firing profile.

19. A method as recited in claim 18 further comprising:

determining which of the candidate skip fire firing profiles is most fuel efficient in delivering the engine output wherein the selection of the operational skip fire firing profile is based on the fuel efficiency determination.

20. A method as recited in claim 18 or 19 wherein:

the plurality of candidate firing fractions includes a first and a second candidate firing fraction;

calculating a first candidate cylinder load such that a combination of the first candidate firing fraction and the first candidate cylinder load delivers the desired engine output and forms a first candidate skip fire firing profile; and

determining whether the first candidate skip fire firing profile is allowed wherein the allowance of the first candidate skip fire firing profile depends in part on whether the first candidate cylinder load exceeds a threshold wherein the threshold varies as a function of engine speed and transmission gear.

21. A method as recited in claim 20 wherein the threshold further varies based on a vehicle operating parameter that is selected from the group consisting of operating gear, road conditions, gear shift, vehicle speed, cabin noise level, presence of engine idle, accelerator pedal position and rate of change in a position of an accelerator pedal.

22. A method as recited in claim 20 or 21 wherein:

if the first candidate skip fire firing profile is not allowed, selecting a new candidate firing fraction and iterating until an allowed skip fire firing profile is found.

23. A method as recited in any of claims 18-22 wherein the selection of the one of the

candidate skip fire firing profile involves using a lookup table that indicates different maximum allowable cylinders loads at different engine speeds and firing fractions.

24. A method as recited in any of claims 18-23 wherein the selection of the one of the candidate skip fire firing profiles is performed on a firing opportunity by firing opportunity basis.

25. A method as recited in any of claims 18-24 wherein the selection of the one of the candidate skip fire firing profiles is performed at least once every engine cycle.

26. A method as recited in any of claims 18-25 further comprising:

determining whether the calculated cylinder load for each of the plurality of candidate firing fraction exceeds a corresponding predetermined maximum allowed cylinder load.

27. A method as recited in claim 26 further comprising:

when it is determined that the cylinder load calculated for a particular candidate firing fraction exceeds the corresponding maximum allowed cylinder load, not using the particular candidate firing fraction to operate the engine.

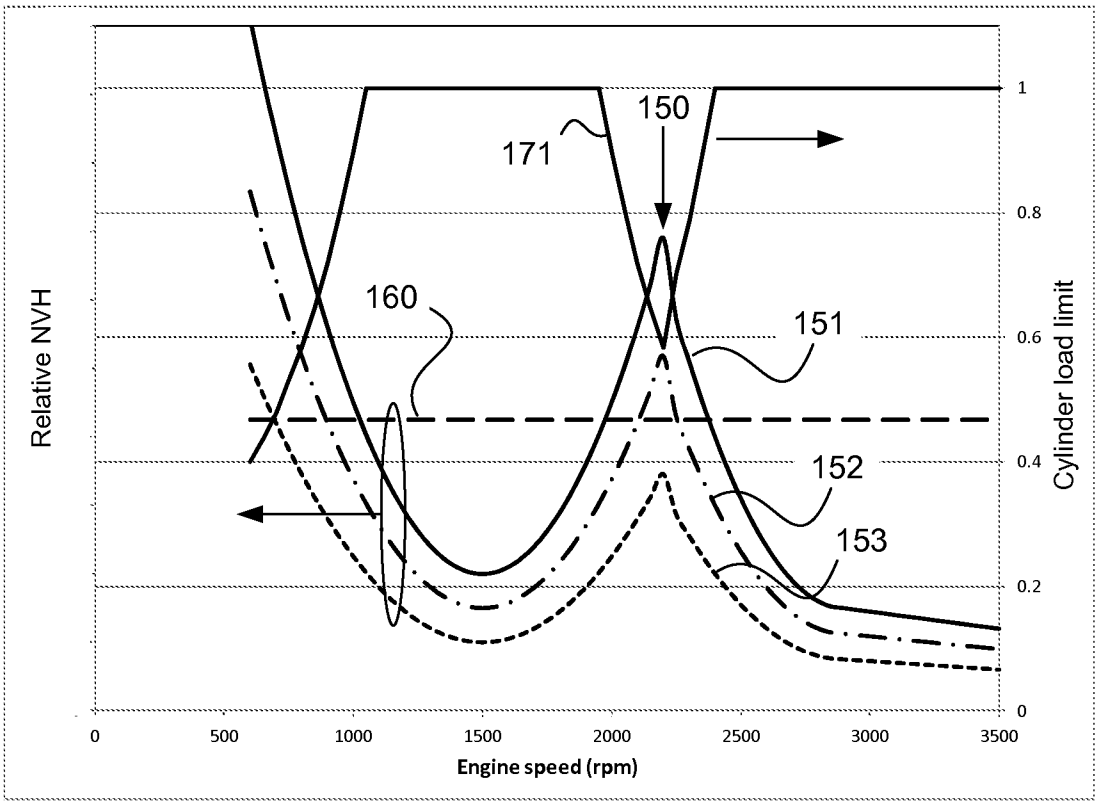

Relative NVH
Cylinder load limit
Engine speed (rpm)
150
171
160
151
152
153
0
500
1000
1500
2000
2500
3000
3500
0
0.2
0.4
0.6
0.8
1

FIG. 1

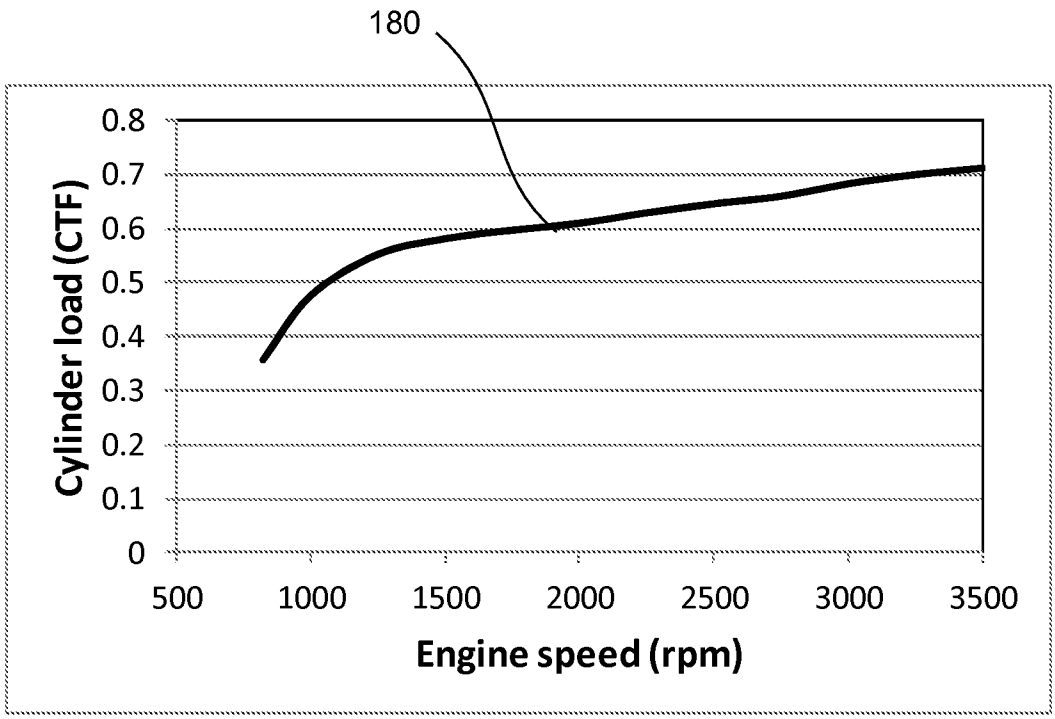
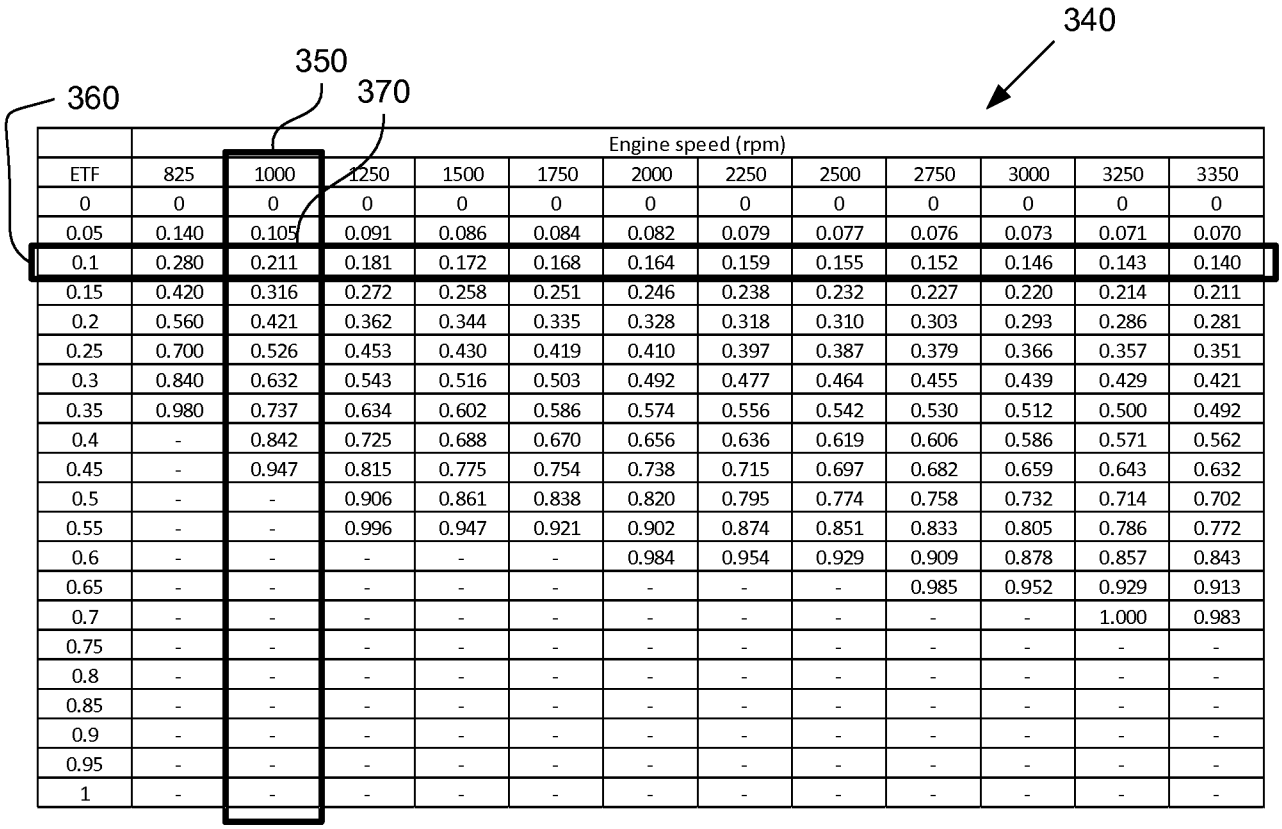

180
Cylinder load (CTF)
Engine speed (rpm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
500
1000
1500
2000
2500
3000
3500

FIG. 2



	Engine speed (rpm)											
ETF	825	1000	1250	1500	1750	2000	2250	2500	2750	3000	3250	3350
0	0	0	0	0	0	0	0	0	0	0	0	0
0.05	0.140	0.105	0.091	0.086	0.084	0.082	0.079	0.077	0.076	0.073	0.071	0.070
0.1	0.280	0.211	0.181	0.172	0.168	0.164	0.159	0.155	0.152	0.146	0.143	0.140
0.15	0.420	0.316	0.272	0.258	0.251	0.246	0.238	0.232	0.227	0.220	0.214	0.211
0.2	0.560	0.421	0.362	0.344	0.335	0.328	0.318	0.310	0.303	0.293	0.286	0.281
0.25	0.700	0.526	0.453	0.430	0.419	0.410	0.397	0.387	0.379	0.366	0.357	0.351
0.3	0.840	0.632	0.543	0.516	0.503	0.492	0.477	0.464	0.455	0.439	0.429	0.421
0.35	0.980	0.737	0.634	0.602	0.586	0.574	0.556	0.542	0.530	0.512	0.500	0.492
0.4	-	0.842	0.725	0.688	0.670	0.656	0.636	0.619	0.606	0.586	0.571	0.562
0.45	-	0.947	0.815	0.775	0.754	0.738	0.715	0.697	0.682	0.659	0.643	0.632
0.5	-	-	0.906	0.861	0.838	0.820	0.795	0.774	0.758	0.732	0.714	0.702
0.55	-	-	0.996	0.947	0.921	0.902	0.874	0.851	0.833	0.805	0.786	0.772
0.6	-	-	-	-	-	0.984	0.954	0.929	0.909	0.878	0.857	0.843
0.65	-	-	-	-	-	-	-	-	0.985	0.952	0.929	0.913
0.7	-	-	-	-	-	-	-	-	-	-	1.000	0.983
0.75	-	-	-	-	-	-	-	-	-	-	-	-
0.8	-	-	-	-	-	-	-	-	-	-	-	-
0.85	-	-	-	-	-	-	-	-	-	-	-	-
0.9	-	-	-	-	-	-	-	-	-	-	-	-
0.95	-	-	-	-	-	-	-	-	-	-	-	-
1	-	-	-	-	-	-	-	-	-	-	-	-

FIG. 3

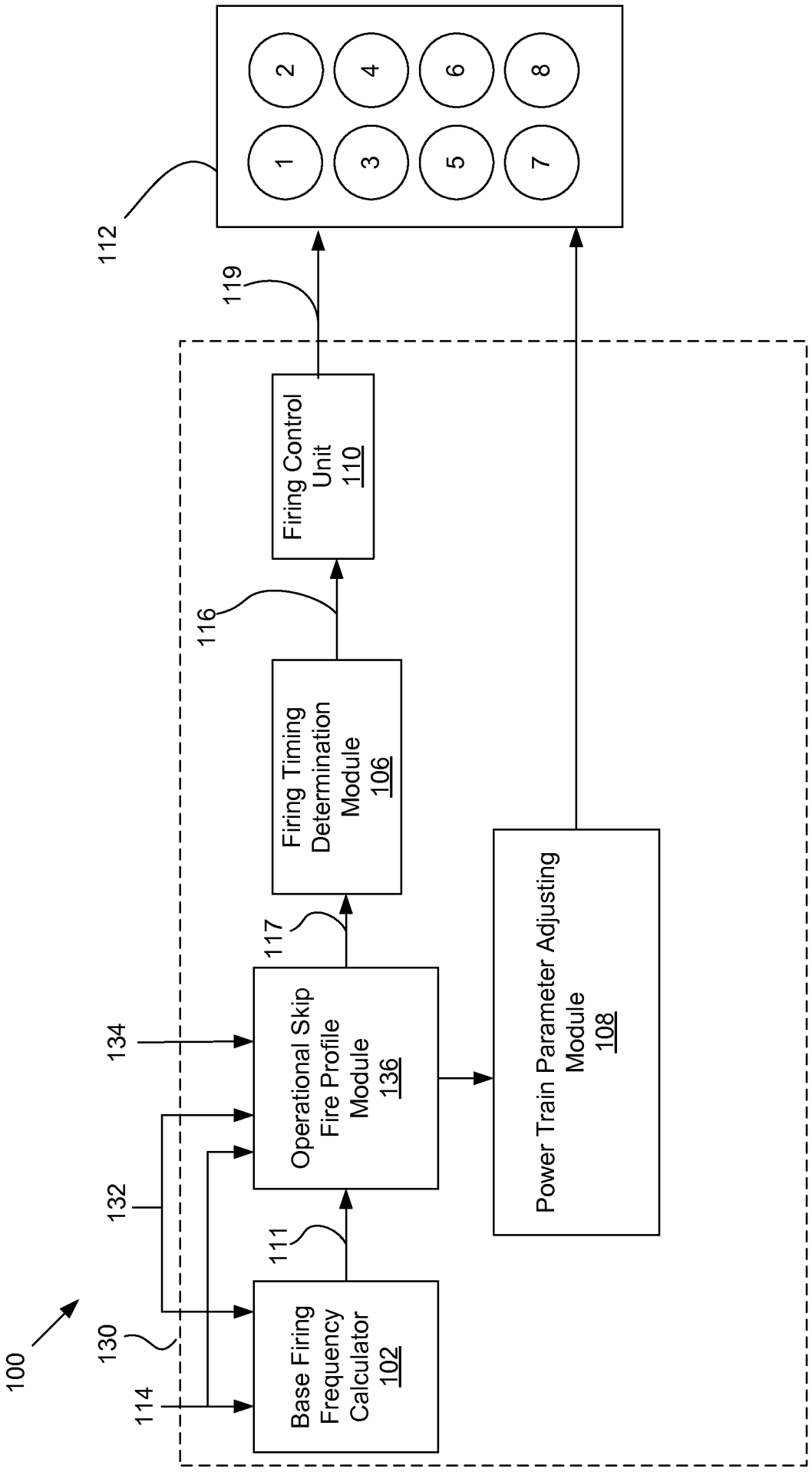

100
130
114
132
134
111
117
119
112
Base Firing Frequency Calculator 102
Operational Skip Fire Profile Module 136
Firing Timing Determination Module 106
Firing Control Unit 110
Power Train Parameter Adjusting Module 108
116
1
2
3
4
5
6
7
8

FIG. 4

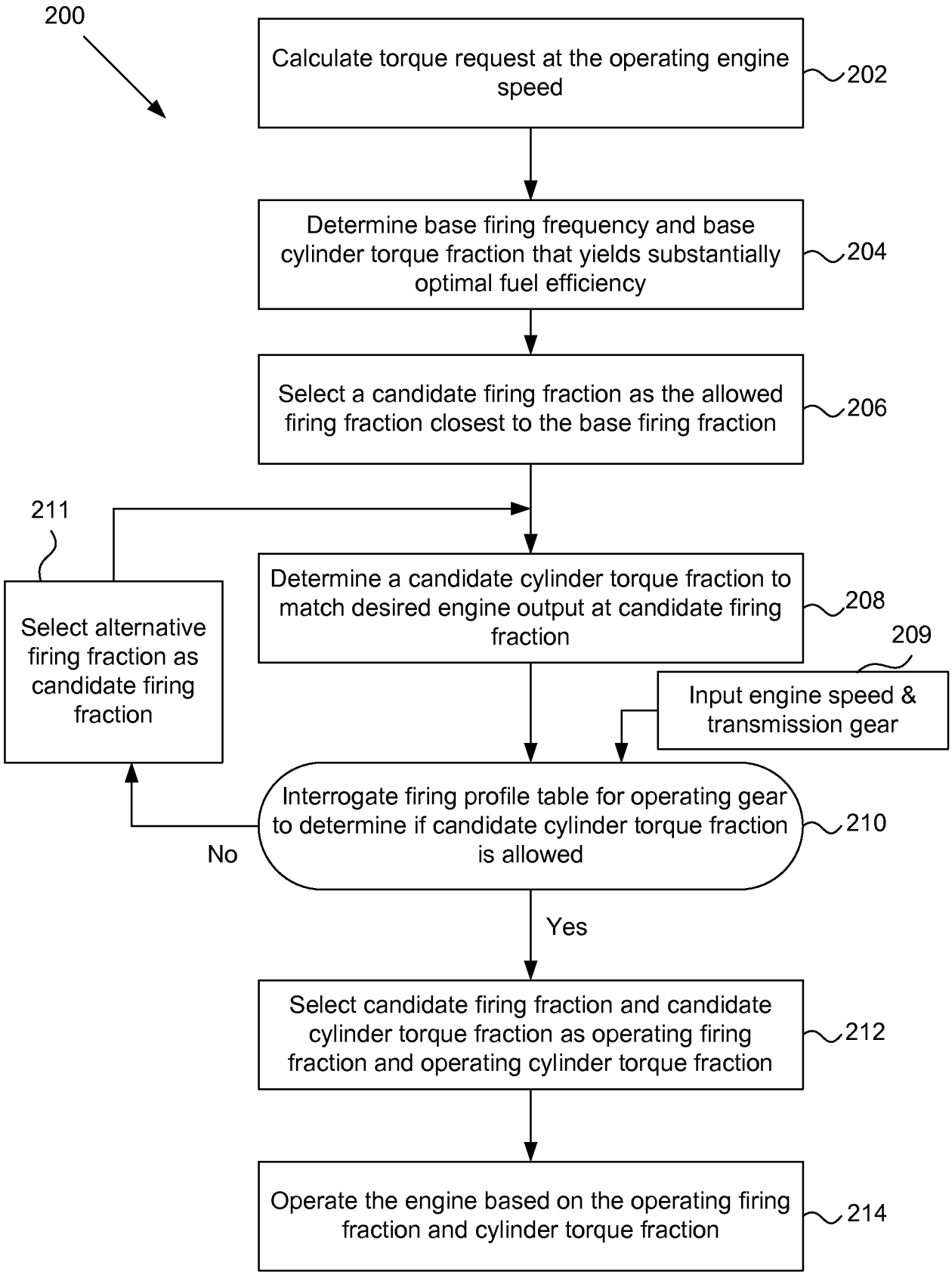
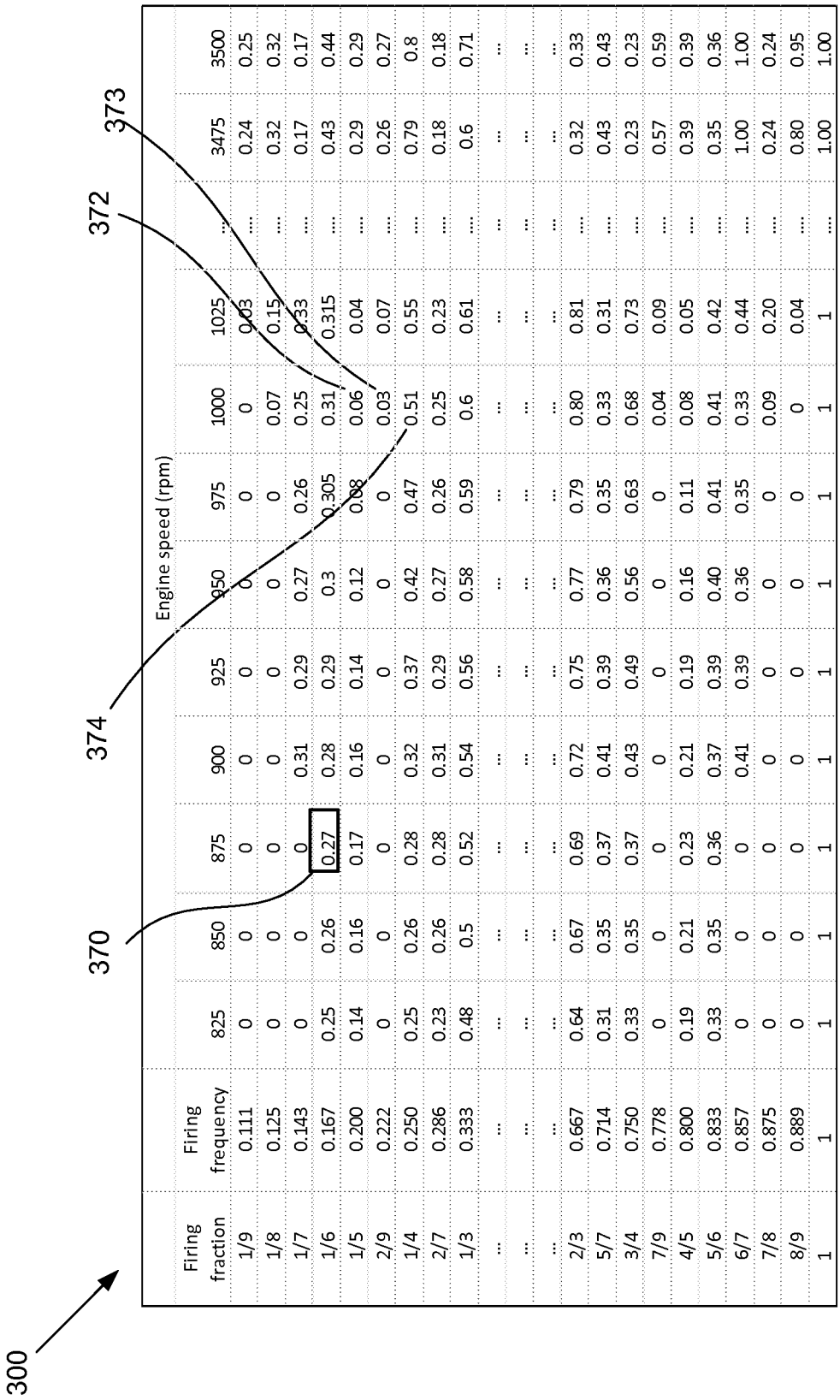
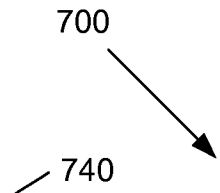

200
Calculate torque request at the operating engine speed
202
Determine base firing frequency and base cylinder torque fraction that yields substantially optimal fuel efficiency
204
Select a candidate firing fraction as the allowed firing fraction closest to the base firing fraction
206
211
Select alternative firing fraction as candidate firing fraction
Determine a candidate cylinder torque fraction to match desired engine output at candidate firing fraction
208
209
Input engine speed & transmission gear
Interrogate firing profile table for operating gear to determine if candidate cylinder torque fraction is allowed
210
No
Yes
Select candidate firing fraction and candidate cylinder torque fraction as operating firing fraction and operating cylinder torque fraction
212
Operate the engine based on the operating firing fraction and cylinder torque fraction
214

FIG. 5



Firing fraction	Firing frequency	825	850	875	900	925	950	975	1000	1025	...	3475	3500
1/9	0.111	0	0	0	0	0	0	0	0	0.03	....	0.24	0.25
1/8	0.125	0	0	0	0	0	0	0	0.07	0.15	....	0.32	0.32
1/7	0.143	0	0	0	0.31	0.29	0.27	0.26	0.25	0.33	....	0.17	0.17
1/6	0.167	0.25	0.26	0.27	0.28	0.29	0.3	0.305	0.31	0.315	....	0.43	0.44
1/5	0.200	0.14	0.16	0.17	0.16	0.14	0.12	0.08	0.06	0.04	....	0.29	0.29
2/9	0.222	0	0	0	0	0	0	0	0.03	0.07	....	0.26	0.27
1/4	0.250	0.25	0.26	0.28	0.32	0.37	0.42	0.47	0.51	0.55	....	0.79	0.8
2/7	0.286	0.23	0.26	0.28	0.31	0.29	0.27	0.26	0.25	0.23	....	0.18	0.18
1/3	0.333	0.48	0.5	0.52	0.54	0.56	0.58	0.59	0.6	0.61	....	0.6	0.71
...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...
2/3	0.667	0.64	0.67	0.69	0.72	0.75	0.77	0.79	0.80	0.81	....	0.32	0.33
5/7	0.714	0.31	0.35	0.37	0.41	0.39	0.36	0.35	0.33	0.31	....	0.43	0.43
3/4	0.750	0.33	0.35	0.37	0.43	0.49	0.56	0.63	0.68	0.73	....	0.23	0.23
7/9	0.778	0	0	0	0	0	0	0	0.04	0.09	....	0.57	0.59
4/5	0.800	0.19	0.21	0.23	0.21	0.19	0.16	0.11	0.08	0.05	....	0.39	0.39
5/6	0.833	0.33	0.35	0.36	0.37	0.39	0.40	0.41	0.41	0.42	....	0.35	0.36
6/7	0.857	0	0	0	0.41	0.39	0.36	0.35	0.33	0.44	....	1.00	1.00
7/8	0.875	0	0	0	0	0	0	0	0.09	0.20	....	0.24	0.24
8/9	0.889	0	0	0	0	0	0	0	0	0.04	....	0.80	0.95
1	1	1	1	1	1	1	1	1	1	1	....	1.00	1.00

FIG. 6



Firing fraction	Firing frequency	Maximum allowed CTF	Range 1		Range 2		Range 3	
			Min. rpm	Max. rpm	Min. rpm	Max. rpm	Min. rpm	Max. rpm
1/4	0.250	0.10	600	3500				
1/4	0.250	0.20	625	850	900	2100	2200	3500
1/4	0.250	0.40	650	750	1050	1800	2300	3500
1/4	0.250	0.60	1100	1700	2300	3500		
1/4	0.250	0.80	1200	1250	1300	1600	2400	3500
1/4	0.250	1.00	1325	1550	2450	3500		
2/7	0.286	0.10	700	1100	1200	2700		
2/7	0.286	0.20	750	1000	1300	2600		
2/7	0.286	0.40	1400	2500				
2/7	0.286	0.60	1500	1600	1800	2500		
2/7	0.286	0.80	1900	2400				
2/7	0.286	1.00	2000	2300				
1/3	0.333	0.10	600	3500				
1/3	0.333	0.20	625	1400	1600	2200	2300	3500
1/3	0.333	0.40	700	1300	1650	2150	2350	3500
1/3	0.333	0.60	1000	1100	1750	2050	2500	3500
1/3	0.333	0.80	1775	2025				
1/3	0.333	1.00	1800	2000				

FIG. 7

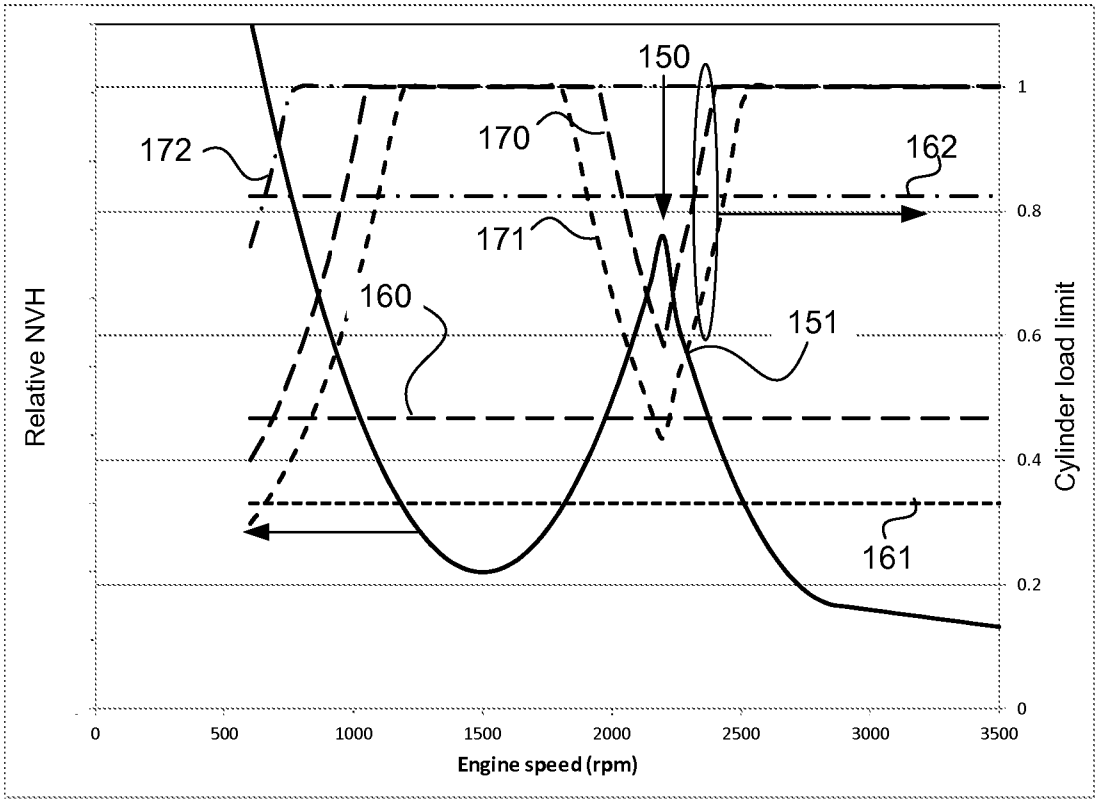

150
172
170
162
171
160
151
161
Relative NVH
Cylinder load limit
Engine speed (rpm)
0
500
1000
1500
2000
2500
3000
3500
0
0.2
0.4
0.6
0.8
1

FIG. 8

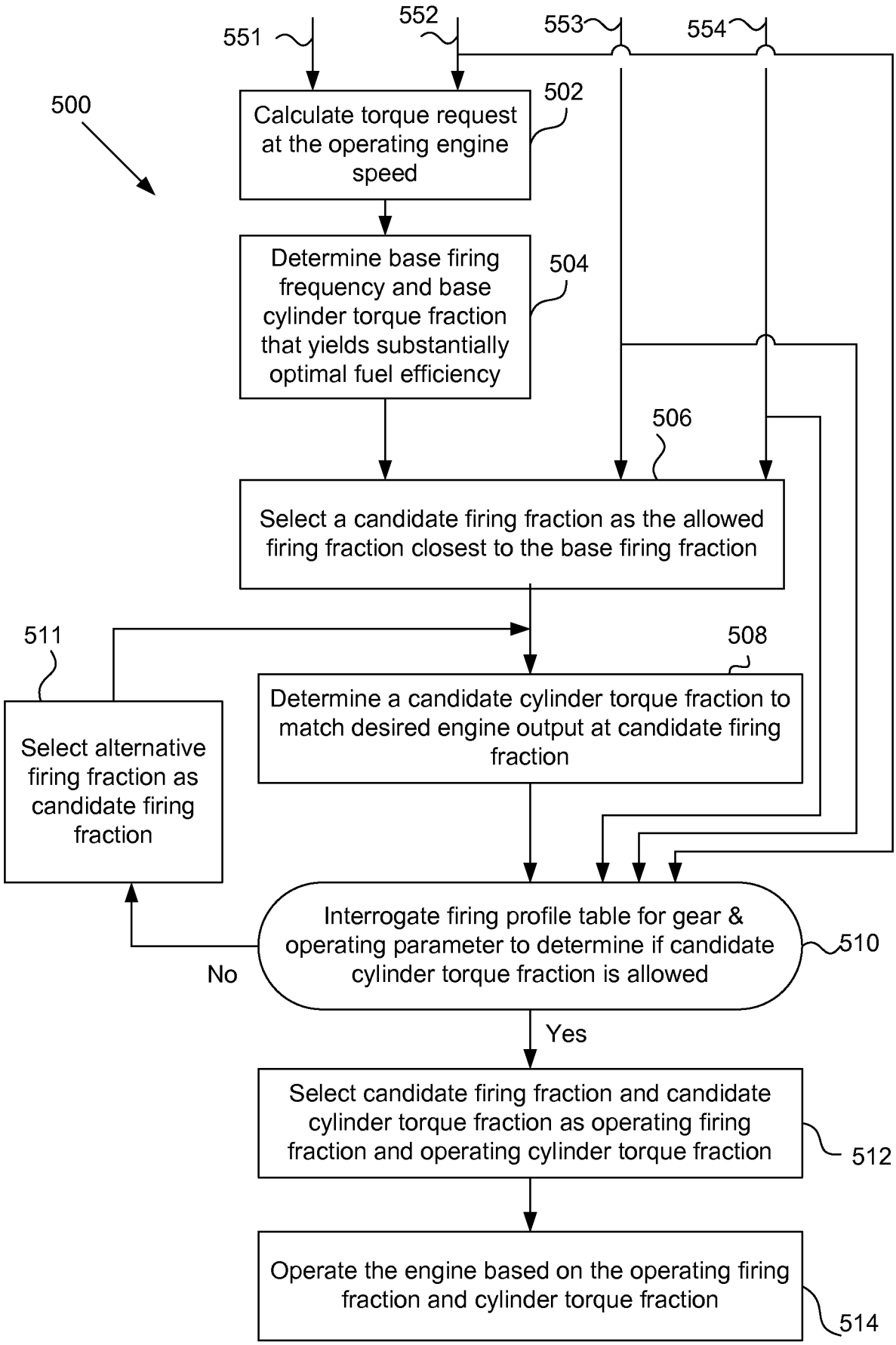

551
552
553
554
500
Calculate torque request at the operating engine speed
502
Determine base firing frequency and base cylinder torque fraction that yields substantially optimal fuel efficiency
504
506
Select a candidate firing fraction as the allowed firing fraction closest to the base firing fraction
511
508
Determine a candidate cylinder torque fraction to match desired engine output at candidate firing fraction
Select alternative firing fraction as candidate firing fraction
Interrogate firing profile table for gear & operating parameter to determine if candidate cylinder torque fraction is allowed
510
No
Yes
Select candidate firing fraction and candidate cylinder torque fraction as operating firing fraction and operating cylinder torque fraction
512
Operate the engine based on the operating firing fraction and cylinder torque fraction
514

FIG. 9

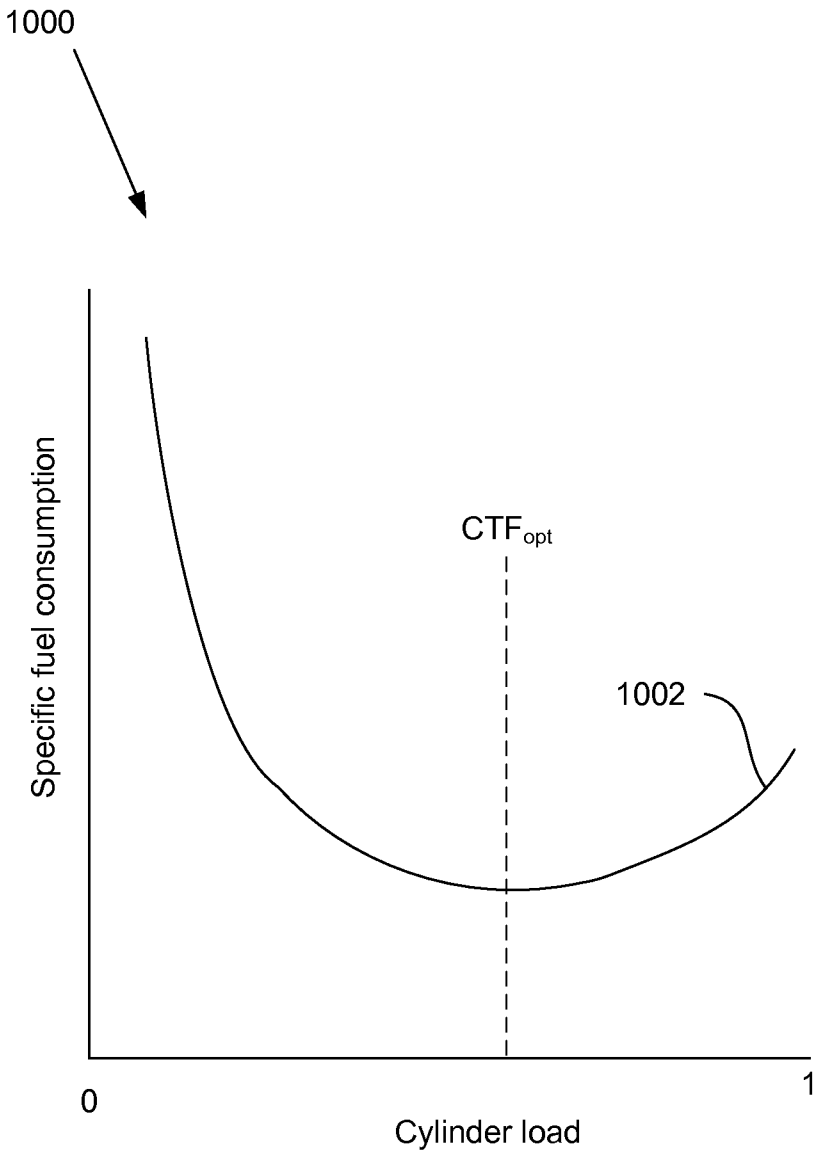

1000
Specific fuel consumption
CTF$_{opt}$
1002
0
1
Cylinder load

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/019496

A. CLASSIFICATION OF SUBJECT MATTER

F02D 17/02(2006.01)i, F02P 9/00(2006.01)i, F02P 5/04(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F02D 17/02; F02D 45/00; F02D 41/00; F02B 33/44; F01N 3/18; F02D 43/00; F02B 77/00; F02P 9/00; F02P 5/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: skip firing, cylinder, determine, control, lookup table, operation, load, and calculate

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010-0100299 A1 (TRIPATHI et al.) 22 April 2010 See abstract; paragraphs [0013]-[0028], [0088]-[0097], [0146]-[0149] and figure 2B.	1-3,9-12,18-21
A	US 2014-0041625 A1 (PIRJABERI et al.) 13 February 2014 See abstract; paragraphs [0009]-[0014] and claims 1-24.	1-3,9-12,18-21
A	US 2013-0289853 A1 (SERRANO, LOUIS J.) 31 October 2013 See abstract; paragraphs [0009]-[0014] and claims 1, 8.	1-3,9-12,18-21
A	US 2012-0285161 A1 (KERNS et al.) 15 November 2012 See abstract; claims 1-20 and figure 7.	1-3,9-12,18-21
A	US 5553575 A (BECK et al.) 10 September 1996 See abstract and claim 1.	1-3,9-12,18-21

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 June 2015 (16.06.2015)	**17 June 2015 (17.06.2015)**

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701, Republic of Korea
Facsimile No. +82-42-472-7140

Authorized officer
HWANG, Chan Yoon
Telephone No. +82-42-481-3347

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/019496

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 5, 27
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claims 5 and 27 are unclear, because they refer to a multiple dependent claim which does not comply with PCT Rule 6.4(a). Threfore, claims 5 and 27 are contrary to PCT Article 6.

3. ☒ Claims Nos.: 4, 6-8, 13-17, 22-26
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2015/019496

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2010-0100299 A1	22/04/2010	CN 102089511 A	08/06/2011
		CN 102089511 B	12/11/2014
		CN 102713215 A	03/10/2012
		EP 2307688 A1	13/04/2011
		EP 2524129 A1	21/11/2012
		JP 2011-527736 A	04/11/2011
		JP 2013-224669 A	31/10/2013
		JP 5395899 B2	22/01/2014
		KR 10-2011-0040920 A	20/04/2011
		TW 201009186 A	01/03/2010
		US 2010-0006065 A1	14/01/2010
		US 2010-0010724 A1	14/01/2010
		US 2010-0037857 A1	18/02/2010
		US 2010-0050985 A1	04/03/2010
		US 2010-0050986 A1	04/03/2010
		US 2011-0030657 A1	10/02/2011
		US 2011-0048372 A1	03/03/2011
		US 7577511 B1	18/08/2009
		US 7849835 B2	14/12/2010
		US 7886715 B2	15/02/2011
		US 7954474 B2	07/06/2011
		US 8131447 B2	06/03/2012
		US 8336521 B2	25/12/2012
		US 8402942 B2	26/03/2013
		US 8511281 B2	20/08/2013
		US 8646435 B2	11/02/2014
		WO 2010-006311 A1	14/01/2010
		WO 2010-006321 A2	14/01/2010
		WO 2010-006321 A3	08/04/2010
		WO 2010-006323 A2	14/01/2010
		WO 2010-006323 A3	08/04/2010
		WO 2011-085383 A1	14/07/2011
US 2014-0041625 A1	13/02/2014	KR 10-2015-0038113 A	08/04/2015
		WO 2014-025939 A1	13/02/2014
US 2013-0289853 A1	31/10/2013	None	
US 2012-0285161 A1	15/11/2012	US 8919097 B2	30/12/2014
US 5553575 A	10/09/1996	CN 1078662 C	30/01/2002
		CN 1187862 A	15/07/1998
		CN 1187862 C	15/07/1998
		WO 97-00378 A1	03/01/1997