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(54) Method of controlling indicated torque for internal combustion engines

(57) The present invention relates to a method of controlling indicated torque for internal combustion engines by means of feedback control, wherein

■ the torque setpoint $T_{ind,setpt}$ is computed from the accelerator pedal position (α_{ped}), the torque losses and, if necessary, additional signals like engine speed, gear and the like,
■ said torque setpoint $T_{ind,setpt}$ is converted into the injection pulse duration (t_{pulse}) within a feedforward path,
■ the in-cylinder pressure p created by burning the fuel injected during injection pulse duration (t_{pulse}) is measured and used for calculating actual indicated torque T_{ind},
■ said actual indicated torque T_{ind} is controlled to the setpoint $T_{ind,setpt}$ via feedback control, i.e., by closing the control loop by means of a feedback path, in order to adjust said actual indicated torque T_{ind},

It is the object of the present invention to provide a method of controlling indicated torque for internal combustion engines by means of feedback control, which ensures consistency for the torque, for all operating modes of the engine and for the transitions between those modes.

With respect to the object a method is provided, which is characterised in that

■ said feedback path is provided by a torque controller which uses, possibly in addition to other signals which describe the engine operating conditions, the deviation ΔT_{ind} between setpoint $T_{ind,setpt}$ and actual value T_{ind} for the indicated torque as an input for updating at least one lookup table storing the manipulated variable, i.e., the correction of said manipulated variable, which is used as output data to adjust said actual indicated torque T_{ind},
■ said additional signals are used for scheduling said at least one lookup table in order to enable a fast controller reaction during transient conditions, when the engine operating conditions are changing such that the correction of the manipulated variable is read out from said at least one lookup table by using the scheduling parameters as input data, and
■ said torque controller is provided with a low bandwidth b due to noise on the measured in-cylinder pressure signal, p, and thus on the calculated torque, T_{ind}, in order to make said manipulated variable less sensitive to the noise of T_{ind} by slowing down the convergence of the actual value T_{ind} for the indicated torque to the setpoint $T_{ind,setpt}$, if deviation ΔT_{ind} is affected substantially by signal noise.

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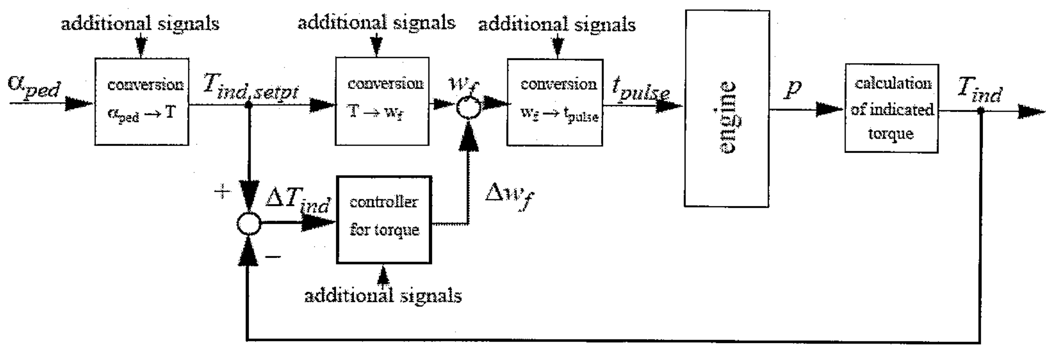

additional signals
α_{ped}
conversion $\alpha_{ped} \rightarrow T$
$T_{ind,setpt}$
additional signals
conversion $T \rightarrow w_f$
w_f
additional signals
conversion $w_f \rightarrow t_{pulse}$
t_{pulse}
engine
p
calculation of indicated torque
T_{ind}
+
ΔT_{ind}
controller for torque
Δw_f
−
additional signals

Fig. 3

Description

[0001] The present invention relates to a method of controlling indicated torque for internal combustion engines by means of feedback control, wherein

- the torque setpoint $T_{ind,setpt}$ is computed from the accelerator pedal position (α_{ped}), the torque losses and, if necessary, additional signals like engine speed, gear and the like,

- said torque setpoint $T_{ind,setpt}$ is converted into the injection pulse duration (t_{pulse}) within a feedforward path,

- the in-cylinder pressure p created by burning the fuel injected during injection pulse duration (t_{pulse}) is measured and used for calculating actual indicated torque T_{ind},

- said actual indicated torque T_{ind} is controlled to the setpoint $T_{ind,setpt}$ via feedback control, i.e., by closing the loop by means of a feedback path, in order to adjust said actual indicated torque T_{ind}.

[0002] Modem control strategies for combustion engines - both diesel and gasoline engines - are using the torque to describe the engine load rather than fuel quantity (diesel) or air mass (gasoline) as in prior strategies.

[0003] For modem torque-based engine control strategies, it is important to ensure that indicated torque is consistent, especially for future, more stringent emissions standards. Indicated torque can be derived from in-cylinder pressure measurements and be used for feedback control.

[0004] Modem control systems for engines often use torque demand *T*, which is generated from accelerator pedal position (α_{ped}) and torque losses, and the engine speed *N* as the most important input data for lookup tables in order to read out from these lookup tables the variable to be controlled (output data), i.e., boost pressure, injection-timing and the like. These input data are utilized by many engine control substructures, for instance to control the boost pressure, the exhaust gas recirculation (EGR) or within a fuel injection control substructure. Within fuel control, torque demand *T* and engine speed *N* are used as input data to read injection-timing, injection duration and fuel mass from the respective lookup tables. Sometimes additional input data have to be taken into account. For example, the rail pressure has to be taken into consideration within the fuel control. The lookup tables are usually stored in an engine control unit (ECU).

[0005] However, torque is usually not measured such that the torque setpoint which is computed from the accelerator pedal position (α_{ped}) and other additional signals such as gear and engine speed is achieved with feedforward control only, as can be seen in Figure 1. The advantage of this feedforward control is that it is very fast. At tip-in, the setpoint for indicated torque $T_{ind,setpt}$ and thus the fuel quantity (w_f) and the injection duration (t_{pulse}) can be changed substantially from one combustion event to the next. However, due to tolerances, aging, and modeling inaccuracies, the torque achieved will never match the setpoint exactly.

[0006] The torque setpoint is first converted into fuel quantity (w_f); this conversion is dependent on many additional signals, such as engine speed, injection or spark timing, engine temperature, etc. Fuel quantity is then converted into the injection duration (t_{pulse}), i.e., the time during which the injector nozzle needs to be open; this conversion depends, among other things, on fuel pressure and immediately preceding injection pulses. The in-cylinder pressure p can be measured and used for calculating indicated torque T_{ind}.

[0007] As can be seen in Figure 2, the torque setpoint generation consists of two parts. The driver asks for a certain torque at the clutch, $T_{clutch,setpt}$, or the wheel by adjusting the pedal position (α_{ped}). The engine must produce a somewhat higher torque in order to compensate for all the torque losses in the engine due to friction and/or auxiliaries such as fuel pump and the like. This higher torque, produced by pressure acting on the piston, is called indicated torque, T_{ind}.

[0008] In the engine, the fuel injected during the injector opening time is burnt and creates increased pressure in the cylinder and the corresponding indicated torque and thus torque at the clutch. If the two conversions from torque setpoint via fuel quantity (w_f) to injection pulse duration (t_{pulse}) were exact inverses of the processes in the engine, the indicated torque T_{ind} produced would be exactly the same as the setpoint for it, i.e., $T_{ind,setpt}$. However, the conversions are never exact. In particular the torque losses are only rough estimate. For driveability, the resulting difference between setpoint and actual torque is not critical (as long as the conversions are smooth and monotonic) because the driver will compensate for it by adjusting the accelerator pedal position (α_{ped}).

[0009] For emissions, though, this torque difference is relevant. For example, the setpoints for exhaust gas recirculation or boost pressure control are calculated from lookup tables in which the engine load is given by the setpoint for the indicated torque, as mentioned above. The torque difference thus means that the setpoints for EGR and boost pressure are not as intended. This is one of the main sources for deviations from the intended emissions levels, and it becomes more significant the more stringent legislation for emissions is.

[0010] Furthermore exhaust gas aftertreatment for modem engines requires sophisticated control strategies for torque, because the aftertreatment makes it necessary to operate the engine in different modes.

[0011] Internal combustion engines have to be provided with various types of aftertreatment devices for purifying exhaust gas generated by the combustion and emitted from combustion chambers into the exhaust pipe. For example, devices to filter and trap the soot particulates contained in the exhaust gas. Within a regenartion phase the particulate filter has to be regenerated and the trapped particulates have to be burned. Thus a mode for the periodic regeneration of the aftertreatment devices is needed. For instance, the soot accumulated in a diesel particulate filter is burned periodically by heating the exhaust gas to rather high temperatures which may be achieved by a combination of intake throttling and post injection. Both of these measures can lead to torque fluctuations or offsets noticeable to the driver and due to this a sophisticated control strategy for torque is required.

[0012] For reducing nitrogen oxides (NO_x) emissions of an internal combustion engine a NO_x storage catalyst could be disposed in the exhaust pipe. Such a catalyst is also known as NO_x trap or lean NO_x trap (abbreviated LNT - Lean NO_x Trap).

[0013] A diesel lean NO_x trap (LNT) adsorbs and stores molecules of nitrogen oxides (NO_x) during the lean operation of the internal combustion engine. When saturated with NO_x molecules, a rich operation phase is required to purge the trap. This allows the release of the stored NO_x molecules and its reduction into non-polluting components, mainly nitrogen (N_2), carbon dioxide (CO_2), and water vapor (H_2O). For NO_x trap purging, the engine must be operated under rich conditions (excess fuel) for a short period of time rather often, and this transition from the conventional lean operation to rich operation again can lead to noticeable torque fluctuations or offsets. Thus a sophisticated control strategy for indicated torque is required.

[0014] Additionally, modem combustion concepts with combustion at low temperature (e.g., HCCI - homogeneous charge compression ignition) involve mode changes as well because low temperature combustion is only possible for low engine load while conventional combustion is needed for higher loads. Also here, the change between the two modes of operation can involve torque fluctuations or offsets, so that with respect to these combustion concepts a sophisticated control strategy for torque is required.

[0015] Thus a problem to be solved is to ensure consistency for the torque, for all operating modes of the engine and for the transitions between those modes.

[0016] One way of dealing with this problem is to use feedback control. Consistency for torque can be achieved, i.e., can be improved in comparison to the feedforward control described above (Figure 1), by closing the loop on indicated torque such that the produced actual indicated torque T_{ind} is controlled to the setpoint $T_{ind,setpt}$.

[0017] For example, such a closed-loop torque control is disclosed in the UK Patent Application GB 2 331 154 A, which relates to a method of determining the injected quantity of fuel in an internal combustion engine, in which the in-cylinder pressure p in a cylinder of the engine is measured by a pressure sensor and the crankshaft angular position is measured by an angular position sensor. The measured pressure p is synchronized with the measured crank angle in order to calculate the indicated work corresponding to the difference between high-pressure work and charge change work. The injected fuel quantity is then ascertained from the calculated indicated work value.

[0018] According to a preferred embodiment disclosed in the UK Patent Application GB 2 331 154 A the torque at the crankshaft is ascertained from the ascertained quantity of fuel and/or the calculated indicated work, i.e., the torque is calculated using the measured in-cylinder pressure p indirectly. The torque at the crankshaft, which is equal to the torque at the clutch T_{clutch}, is compared with a setpoint T_{setpt} ascertained from the gas pedal position *(α_{ped})*, in order to determine the difference ΔT between the actual torque at the crankshaft T_{clutch} and the setpoint T_{setpt}, which is used to adjust the injected fuel quantity in such a way that the difference ΔT is reduced.

[0019] But the UK Patent Application in question does not provide more detailed information on how to control indicated torque for combustion engines by means of feedback control, although feedback control is suggested. Furthermore this application does not refer to specific operating modes of the engine and does not refer to the transitions between those modes.

[0020] With respect to this it is an object of the present invention to provide a method of controlling indicated torque for internal combustion engines by means of feedback control according to the preamble of claim 1, which overcomes the problems described above, in particular a method which ensures consistency for the torque for all operating modes of the engine and for the transitions between those modes.

[0021] According to the present invention and with respect to the object, a method of controlling indicated torque for internal combustion engines by means of feedback control is provided, in which

- the torque setpoint $T_{ind,setpt}$ is computed from the accelerator pedal position *(α_{Ped})*, the torque losses and, if necessary, additional signals like engine speed, gear and the like,
- said torque setpoint $T_{ind,setpt}$ is converted into the injection pulse duration *(t_{pulse})* within a feedforward path,
- the in-cylinder pressure p created by burning the fuel injected during injection pulse duration *(t_{pulse})* is measured and used for calculating actual indicated torque T_{ind},
- said actual indicated torque T_{ind} is controlled to the setpoint $T_{ind,setpt}$ via feedback control, i.e., by closing the control loop by means of a feedback path, in order to adjust said actual indicated torque T_{ind}, and

which is characterised in that

- said *feedback path* is provided by a torque controller which uses, possibly in addition to other signals which describe the engine operating conditions, the deviation ΔT_{ind} between setpoint $T_{ind,setpt}$ and actual value T_{ind} for the indicated torque as an input for updating at least one lookup table storing the manipulated variable, i.e., the correction of said manipulated variable, which is used as output data to adjust said actual indicated torque T_{ind},

- said additional signals are used for scheduling said at least one lookup table in order to enable a fast controller reaction during transient conditions, when the engine operating conditions are changing such that the correction of the manipulated variable is read out from said at least one lookup table by using the scheduling parameters as input data, and

- said torque controller is provided with a low bandwidth b due to noise on the measured in-cylinder pressure signal, p, and thus on the calculated torque, T_{ind}, in order to make said manipulated variable less sensitive to the noise of T_{ind} by slowing down the convergence of the actual value T_{ind} for the indicated torque to the setpoint $T_{ind,setpt}$, if deviation ΔT_{ind} is affected substantially by signal noise.

[0022] The deviation ΔT_{ind} between setpoint $T_{ind,setpt}$ and actual value T_{ind} for the indicated torque can be corrected with feedback control according to the inventive method, as can be seen in Figure 3, which shows a first embodiment according to the inventive method and which will be described in detail below.

[0023] If the controller could be sufficiently fast to correct deviations from one event to the next, no feedforward part would be needed, in fact. However, convergence must be much slower because there is considerable signal noise on the measured indicated torque T_{ind}. This is partially due to the stochastic nature of combustion and unavoidable errors, i.e., fluctuations, in measurements. But still the feedback corrections must be fast and precise when the engine operating point is changed, i.e., when engine operating conditions are changing.

[0024] According to the inventive method, the controller is equipped with a low bandwidth b such that the changes of said manipulated variable are damped, if deviation ΔT_{ind} is affected substantially by signal noise. For this it is preferred, that the bandwidth b is lower than each of the frequencies f_i with large magnitude in the spectrum of the calculated, i.e., measured indicated torque T_{ind} (Fourier analysis). At steady torque, T_{ind} is recorded and then Fourier transformed. The resulting spectrum shows which frequencies are present - ideally only 0 Hz, since it is steady state; any other frequencies with large magnitude result from signal noise. Thus, the relation between the bandwidth b and the frequencies f_i is described by the following expression: $b < f_i$. Because of this setup the controller acts like a low-pass filter with respect to the signal noise. Hence the controller is enabled to deal with the signal noise.

[0025] On the other hand the bandwidth b of the torque controller is maybe too low for sufficiently fast reactions during transients. To overcome this problem, the controller is scheduled on relevant parameters, i.e., variables, preferably on signals describing the engine operation conditions, in particular engine speed N and load $T_{ind,setpt}$ and/or engine temperature (ϑeng), for example. Thus, at each operating point described by these scheduling variables, the manipulated variable, i.e., the correction of the manipulated variable, can be read out from said at least one lookup table as output data by using the scheduling parameters as input data. This enables a fast controller reaction during transient conditions. The bandwidth b can be scheduled, too.

[0026] The controller can adapt slowly, and when a fast change to a different operating condition occurs, the controller can quickly change to those controller states, i.e., locations in the lookup table, which had been adapted slowly during a previous visit of that operating point. With respect to that issue it is referred to the application 05102979.1 filed by the Ford Global Technologies, LLC.

[0027] This application relates to a method for automatically adapting lookup tables, in particular for use in a control unit for an internal combustion engine, wherein the lookup table is a one-dimensional or multi-dimensional point-based lookup table with $n \geq 1$ indexing parameters x as input data and in which the output data are stored at the points.

[0028] There are two options for implementing the torque controller. It can either operate on indicated torque averaged for the n_{cyl} cylinders or, as preferred, such a controller can be implemented for each individual cylinder, which allows for the correction of cylinder imbalance. This has additional advantages for reducing vibrations, noise, and emissions.

[0029] A preferred embodiment of the method is characterised in that a PI-controller is used as torque controller, which is characterised by controller parameters K_P and K_I or an 1-controller is used as torque controller, which is characterised by controller parameters K_I. The character P denotes the proportional part (P-part) and the character I denotes the integral part (1-part) of the controller.

[0030] For these controllers, only the integrator variable constitutes the controller state which needs to be scheduled, whereas the P part adapts instantaneously to new operating conditions and thus does not need to be scheduled. Therefore embodiments of the method are preferred which are characterised in that only the integrator variable is scheduled.

[0031] A preferred embodiment of the method is characterised in that at least one of the controller parameters Kp and/or K_I is schedulded. The controller parameters (K_P, K_I) are preferably scheduled if the bandwidth b of the controllers needs to be operating point dependent.

[0032] The feedforward path in Figure 3, which is the same as the path in Figure 1, converts the torque setpoint $T_{ind,setpt}$ into injector opening durations *(t_{pulse})* for the individual injection pulses. This can either be done in a one-step conversion or, as indicated in the figures, in two steps.

[0033] A preferred embodiment of the method is characterised in that said conversion from torque setpoint $T_{ind,setpt}$ to injection pulse duration *(t_{pulse})* is a two-step conversion.

[0034] The first conversion from torque $T_{ind,setpt}$ to fuel quantity *(w_f)* is done with a model of the combustion in the cylinder in mind, for example. The pressure p in the cylinder is a function of the fuel quantity (w_f), the injection timing and whether there are other injections during compression prior to the main injection(s), the engine speed, the engine and the intake air temperature, the gas composition (EGR level), the intake manifold pressure, and other parameters. Most of these parameters are controlled as a function of engine speed *N* and load described by torque *T*, for example. Thus, it is sufficient to store the fuel mass (w_f) in speed *N* and load $T_{ind,setpt}$ dependent lookup tables which can be switched or interpolated based on engine temperature (ϑ_{eng}) additionally (Figure 5). This modus operandi corresponds to modem control systems. As pointed out in the introduction modem control systems for engines often use torque demand $T_{ind,setpt}$ and engine speed *N* as input data for lookup tables in order to read out from these lookup tables the manipulated variable, i.e., the fuel mass (w_f) for the conversion discussed here.

[0035] The second conversion from fuel mass (w_f) to injection duration (t_{pulse}) is essentially a lookup table with fuel mass (w_f) and fuel pressure p_{fuel} - across the nozzle or in a common rail - as input data and the injection duration (t_{pulse}) as output data.

[0036] Another preferred embodiment of the method is characterised in that said conversion from torque setpoint $T_{ind,setpt}$ to injection pulse duration (t_{pulse}) is a one-step conversion. Since fuel pressure p_{fuel} is a function of engine speed *N* and load $T_{ind,setpt}$ as well, it is sufficient to use a structure similar to that shown in Figure 5 for the one-step conversion as illustated in Figure 6. Within the one-step conversion injection pulse duration *(t_{pulse})* is stored in lookup tables, in which speed *N* and load $T_{ind,setpt}$ are used as input data, so that said torque setpoint $T_{ind,setpt}$ can be converted to injection pulse duration *(t_{pulse})* directly, i.e., in one step.

[0037] A preferred embodiment of the method is characterised in that said at least one lookup table of said controller is scheduled in a similar way as the at least one lookup table used for conversion within the feedforward path, i.e., by using the same scheduling variables. This simplifies implementation of the inventive method.

[0038] A preferred embodiment of the method is characterised in that said at least one lookup table of said controller is stored in a permanent memory unit. While the engine is stationary at a certain operating point, the corresponding controller state, i.e., location or point in the lookup table, is active and can control torque by changing its value slowly. As soon as a change of the engine operating point is requested by the driver, the corresponding controller state, i.e., point in the lookup table, is activated while the previously active state of the controller is frozen such that it can be used again the next time it becomes active. This allows for instantaneous switching between corrections, i.e., values for the manipulated variable (for example Δw_f), which themselves have been found by controllers with a sufficiently low bandwidth.

[0039] When the ECU is shut down, all the controller state variables, i.e., said at least one lookup table need to be stored in permanent memory such that they are available the next time the ECU is booted.

[0040] The inventive method is also used to deal with different modes and the transitions between modes. The modes and the transitions between them are used like an additional scheduling variable or a separate set of lookup tables is used for each mode or transition. The set of scheduling variables may be different for different modes, and for the transitions.

[0041] A preferred embodiment of the method is characterised in that for controlling torque during a specific engine mode said engine mode is used as an additional scheduling variable for said at least one lookup table. Said specific engine mode can be the HCCI mode with combustion at low temperature, the diesel particulate filter regeneration mode, the lean NO_x purging mode or others. Furthermore said specific engine mode can be used for scheduling the controller parameters, namely K_P and/or K_I, and/or the bandwidth *b*.

[0042] It is preferred that for controlling torque during a specific engine mode, a specific set of at least one lookup table assigned to said engine mode is used. So, if the engine operates in m different modes the controller comprises or has access to m different sets of at least one lookup table.

[0043] In order to avoid switching between different storage locations in the at least one lookup table for any of said modes at idle operation of the engine, it is preferred to have separate lookup tables used if the engine is at idle speed. If the at least one lookup table used during normal operation in a mode is also used at idle, it may happen that the torque controller adversely interacts because of the switching between different storage locations.

[0044] A preferred embodiment of the method is characterised in that for controlling torque during a transition between different engine modes, said specific transition is used as an additional scheduling variable for said at least one lookup table. Modem engines often require a mode change due to the aftertreatment devices provided for cleaning the exhaust gas. Devices to filter and trap the soot particulates contained in the exhaust gas require a regeneration phase, for instance by heating the exhaust gas to rather high temperatures which may be achieved by a mode change. Other examples for transitions between different engine modes are already mentioned in the introduction. Furthermore said specific transition can be used for scheduling the controller parameters, namely K_P and/or K_I, and/or the bandwidth *b*.

[0045] In general, if it is pointed out that said at least one lookup table is scheduled, that means the controller is scheduled such that controller parameters, the bandwidth *b* and/or the like are scheduled or can be scheduled, too

[0046] A preferred embodiment of the method is characterised in that for controlling torque during a transition between different engine modes, a specific set of at least one lookup table assigned to said specific transitions is used.

[0047] In general, it may be necessary to use different lookup tables, controller parameter, bandwidth b and the like for the two directions of the mode transitions.

[0048] With respect to the four embodiments mentioned before, an embodiment of the method is preferred which is characterised in that for controlling torque during a transition between different engine modes or during a specific engine mode said at least one lookup table is scheduled on variables, i.e., parameters describing said transition or said specific engine mode. By doing this, variables are used for scheduling which effect the specific engine mode or transition in question.

[0049] A preferred embodiment of the method is characterised in that for controlling torque during a transition between different engine modes, said manipulated variable, i.e., the correction of the manipulated variable, is found by interpolation using the lookup tables of said different engine modes, which can be the normal mode and the filter regeneration mode, for example.

[0050] This constitutes an alternative and quite different approach to the methods described before using specific lookup tables for transition. The transition is achieved by interpolating between the lookup tables for the two different engine modes, between which the engine operation is changed. The interpolation is preferably based on an auxiliary variable. For instance, progress on a time ramp or progress on the transition of the signal which effects the mode change (p_i or $w_{f,post}$ for example). If linear interpolation is not good enough, interpolation factors may be adapted in closed-loop operation.

[0051] Modem engines often undergo operation mode changes, which may because of exhaust gas aftertreatment devices which periodically need special conditions, or may because of an especially advantageous operating mode of the engine (e.g., HCCI) can only be run at low load such that a transition to conventional operation is necessary when higher load is demanded. If such mode changes are controlled in a feedforward manner, they usually lead to some torque fluctuations, which might be noticeable to the driver, and the calibration of these controllers is very tedious because it involves the careful coordination of two or more actuators.

[0052] By using the inventive method with feedback control of torque, the torque fluctuations can be suppressed, and calibration can be simplified substantially. But again the mode changes are too fast for being controlled with an unscheduled controller, because the controller bandwidth b has to be low. A fast controller reaction can be achieved by using a scheduled controller as described above, but with different scheduling parameters. Instead or in addition to the variables used during engine operation in the modes, those variables which effect the mode change and are relatively slow are used for scheduling, while - as example for a manipulated variable - fueling, which can be changed instantaneously, is used to keep torque at the setpoint.

[0053] In the following some examples are given which make the method applied more apparent. The general idea behind all these examples is to schedule the controller on - for example - engine speed *N* and load *T* and on those variables which are used to effect the mode change and are changing considerably more slowly than the manipulated variable used to control the torque (for example fueling w_f and Δw_f) or an auxiliary variable which is used to deploy those variables. The use of such an auxiliary variable has the advantage that the complexity of and memory requirement for the scheduled controller can be reduced: only one additional scheduling variable is used in addition to engine speed and load rather than two or more.

[0054] A preferred embodiment of the method is characterised in that during the transition to and/or from diesel particulate filter regeneration mode, intake manifold pressure p_i and additional fuel mass $w_{f,post}$ injected during at least one post injection are used as scheduling variables, i.e., for scheduling the at least one lookup table.

[0055] For the regeneration of a diesel particulate filter (DPF), the exhaust gas must reach rather high temperatures of about 550 °C which are not reached under normal engine operation. Thus, the engine must be operated in a special DPF regeneration mode for the regeneration. According to one embodiment for regeneration mode, the air intake is throttled - in order to reduce the intake manifold pressure p_i and the air mass flow - and additional fuel $w_{f,post}$ is injected after the main injection during a so-called post injection. Both measures lead to changes in torque if the main fuel injection - and, if existing, pilot fuel injection - is kept constant.

[0056] DPF regenerations are only initiated when the engine is no longer very cold. Hence, there may be no need for scheduling the controller on engine temperature (ϑ_{eng}). But - by applying the above mentioned transition mode - torque fluctuates as a function of intake manifold pressure p_i and post injection quantity $w_{f,post}$, such that these two signals, i.e., variables, are used for scheduling, in addition to engine speed *N* and load *T,* for example. With each mode transition the engine has gone through, the torque fluctuations are reduced further, because the at least one lookup table used is adapted and updated during operation.

[0057] Of course, it is possible to use only one of the two mentioned scheduling variables, especially if one is controlled as a function of the other such that there is only one truly independent variable during the mode transition. Alternatively, an auxiliary variable could be introduced which is then used to control intake manifold pressure p_i and post injection quantity $w_{f,post}$ and which is also utilized as the scheduling variable for the torque controller. This auxiliary variable could for instance be the time elapsed in time-based ramps governing the transition between modes.

[0058] A preferred embodiment of the method is characterised in that during transition from normal, lean operation to rich operation for purging a LNT and/or back, said at least one lookup table is scheduled on EGR level or mass air flow, intake manifold pressure p_i, and/or post-injection fuel quantity $w_{f,post}$.

[0059] NO_x traps are exhaust gas aftertreatment devices which accumulate and store NO and NO_2 during some 100 seconds and then need to be operated with a lack of oxygen and an excess of hydrocarbons for a few seconds for the purging reactions to take place. The change from the normal, lean operation of a diesel engine to rich operation can be achieved by increased levels of EGR, intake air throttling and/or post-injection(s) of additional fuel. This transition is accompanied by torque fluctuations. This is aggravated by the fact that the transitions need to be rather fast in order to avoid the desorption of NO_x and slippage of CO and HC if the conditions for conversion are not right yet.

[0060] The torque controller, i.e., said at least one lookup table and/or controller parameters and/or the bandwidth b for this mode transition is scheduled preferably on EGR level or mass air flow, intake manifold pressure, and/or - if the post-injection is early enough for producing torque - on post-injection fuel quantity, besides engine speed *N* and load *T*. Alternatively, it could again be scheduled on an auxiliary variable (e.g., a time ramp) which is used to deploy the other three signals.

[0061] If the injection pulses are moved towards late injections, it is important to use the main torque producing injection, i.e., the one closest to top dead center (TDC) for fuel mass corrections.

[0062] A preferred embodiment of the method is characterised in that during the transition to and/or from HCCI-mode, said at least one lookup table is scheduled on EGR level and intake air temperature t_i.

[0063] Combustion concepts which apply HCCI combustion at part load need to switch to conventional diesel combustion to reach full load. HCCI combustion is achieved by changes to the EGR level, the compression ratio (possibly done with variable valve timing - VVT), the intake air temperature t_i, and the injection timing. Of these measures, VVT and injection timing changes can be instantaneous, but the other two are slower such that they are suitable as scheduling variables for the torque controller, i.e., for the at least one lookup table and/or controller parameters and/or the bandwidth *b*.

[0064] Alternatively, an auxiliary variable could be introduced again which is used to deploy the HCCI controlling signals and to schedule the torque controller.

[0065] Various embodiments of the present invention will be described below with reference to the Figures 3 to 11:

Figure 1	shows schematically feedforward control of torque according to a conventional strategy known in the state of the art,
Figure 2	shows a method for torque setpoint generation,
Figure 3	shows schematically a first embodiment according to the inventive method of controlling indicated torque by means of feedback control,
Figure 4	shows schematically a second embodiment according to the inventive method of controlling indicated torque by means of feedback control,
Figure 5	shows the first step within a two-step conversion from torque setpoint $T_{ind,setpt}$ to injection pulse duration (t_{pulse}),
Figure 6	shows a one-step conversion from torque setpoint $T_{ind,setpt}$ to injection pulse duration (t_{pulse}),
Figure 7	shows a first embodiment of a torque controller disposed in the feedback path shown in Figure 3,
Figure 8	shows a second embodiment of a torque controller disposed in the feedback path shown in Figure 4,
Figure 9	shows an embodiment of a torque controller disposed in the feedback path and used during mode change for diesel particulate filter regeneration,
Figure 10	shows schematically an 1-controller used as torque controller disposed in the feedback path, and
Figure 11	shows schematically an PI-controller used as torque controller disposed in the feedback path.

[0066] Figures 1 and 2 are already described within the introduction in order to point out the known methods according to the state of the art and the problems resulting from this.

[0067] Figures 3 shows schematically a first embodiment according to the inventive method of controlling indicated torque by means of feedback control.

[0068] The torque setpoint $T_{ind,setpt}$ is computed from the accelerator pedal position (α_{ped}). The torque losses (not shown) are taken into consideration and, if necessary, additional signals like engine speed, gear and the like. Within the feedforward path, the torque setpoint $T_{ind,setpt}$ is converted to injection pulse duration (t_{pulse}). According to the illustrated embodiment this conversion is a two-step conversion.

[0069] The first conversion step relates to the conversion from torque T to fuel quantity (w_f), whereas the second conversion step converts fuel mass (w_f) to injection duration (t_{pulse}).

[0070] The in-cylinder pressure p created by burning the fuel injected during injection pulse duration (t_{pulse}) is measured and used for calculating actual indicated torque T_{ind}, which is controlled to the setpoint $T_{ind,setpt}$ by means of feedback control, i.e., by closing the loop by means of a feedback path, in order to adjust said actual indicated torque T_{ind}.

[0071] A torque controller is disposed in the feedback path. The controller uses, in addition to other signals describing the engine operating conditions, the deviation ΔT_{ind} between setpoint $T_{ind,setpt}$ and actual value T_{ind} for the indicated torque as an input for reading out from and updating at least one lookup table the correction (Δw_f) of the manipulated variable (w_f). According to the embodiment in question, the manipulated variable is fuel mass (w_f). The correction (Δw_f) of the fuel mass (w_f) is added to the fuel mass (w_f) generated within the feedforward path in order to adjust said actual indicated torque T_{ind} by modifying fuel mass quantity (w_f).

[0072] Instead of using only fuel mass (w_f) for controlling torque, the control authority can be extended to use fuel mass and injection timing in a staggered way. For instance, the output of the controller may be a normalized signal from -2 to 2 which is, as long as it is between —1 and 1, translated into fuel mass corrections within the permissible range; for signals in [-2...-1, 1...2], the fuel mass correction is saturated and injection timing is used to further influence the indicated torque. In order to avoid adverse interaction of waves in the common rail, it is suggested to move all the injections for the given cylinder simultaneously.

[0073] Figure 4 shows schematically a second embodiment according to the inventive method of controlling indicated torque by means of feedback control.

[0074] In contrast to the method illustrated in Figure 3, the manipulated variable is the injection pulse duration (t_{pulse}) and thus the output data read out from the at least one lookup table is the correction (Δt_{pulse}) of the injection pulse duration (t_{pulse}). The correction (Δt_{pulse}) of the manipulated variable (t_{pulse}) is added to the injection pulse duration (t_{pulse}) generated within the feedforward path in order to adjust said actual indicated torque T_{ind} by modifying injection pulse duration (t_{pulse}).

[0075] Figure 5 shows the first step within a two-step conversion from torque setpoint $T_{ind,setpt}$ to injection pulse duration (t_{pulse}), which takes place within the feedforward path as can be seen in Figures 3 and 4.

[0076] The first step of the two-step conversion relates to the conversion from torque $T_{ind,setpt}$ to fuel quantity (w_f). As mentioned before, a model of the combustion can be used in which the in-cylinder pressure p is a function of fuel quantity (w_f) and engine temperature (ϑ_{eng}), which are controlled as a function of engine speed N and load $T_{ind,setpt}$.

[0077] Because of this, fuel mass (w_f) is stored in speed N and load $T_{ind,setpt}$ dependent lookup tables which are switched or interpolated based on engine temperature (ϑ_{eng}). In other words, a three-dimensional lookup table is used, in which engine speed N, torque demand $T_{ind,setpt}$ and engine temperature (ϑ_{eng}) are used as input data in order to read out from this lookup table the variable of interest, i.e., the fuel mass (w_f) to be injected during injection pulse duration (t_{pulse}). Figure 6 shows a one-step conversion from torque setpoint $T_{ind,setpt}$ to injection pulse duration (t_{pulse}), which takes place within the feedforward path and can be applied instead of the two-step conversion illustrated in Figure 5.

[0078] Taking into account that the second conversion within a two-step conversion relates to the conversion from fuel mass (w_f) to injection duration (t_{pulse}), for which a lookup table scheduled on fuel mass (w_f) and fuel pressure p_{fuel} can be used, and furthermore taking into account that fuel pressure p_{fuel} is a function of engine speed N and load $T_{ind,setpt}$, it is sufficient to use a structure similar to that shown in Figure 5 for the one-step conversion as illustated in Figure 6.

[0079] Within the one-step conversion, injection pulse duration (t_{pulse}) is stored in lookup tables scheduled on engine speed N and load $T_{ind,setpt}$, which are switched or interpolated based on engine temperature (ϑ_{eng}), so that said torque setpoint $T_{ind,setpt}$ can be converted to injection pulse duration (t_{pulse}) directly, i.e., in one step.

[0080] Figure 7 shows a first embodiment of a torque controller disposed in the feedback path shown in Figure 3.

[0081] The illustrated torque controller uses the deviation ΔT_{ind} between setpoint $T_{ind,setpt}$ and actual value T_{ind} for the indicated torque in addition to engine speed N and torque setpoint $T_{ind,setpt}$ as input data for reading out from and updating in lookup tables based on engine temperature (ϑ_{eng}) the correction (Δw_f) of the manipulated variable (w_f) as output data, in order to enable a fast controller reaction during transient conditions when the engine operating conditions are changing. Consequently, the lookup table used is scheduled on engine speed N, torque setpoint $T_{ind,setpt}$ and engine temperature (ϑ_{eng}) and because of this, the lookup table used is a three-dimensional one.

[0082] The scheduling variables can also be used for scheduling the controller parameters, namely K_P and/or K_I, and/or the bandwidth b.

[0083] Feedback corrections must be fast and precise when the engine operationg conditions are changed. This is achieved by scheduling the controller in a similar way as the at least one lookup table used for conversion within the feedforward path. While the engine is stationary at a certain operating point, the corresponding controller, i.e., a certain location in one of the various lookup tables, is active and can control torque by changing its internal state slowly. As soon as a change of the engine operating point is requested by the driver, the respective controller, i.e., the respective location in the respective lookup table corresponding to the actual engine operating condition, is activated while the state of the previously active controller is frozen such that it can be used again the next time that controller, i.e., that location, becomes active.

[0084] Changing engine operation conditions could result either in changing the lookup table corresponding to said actual engine temperature (switching based on engine temprature) due to a change in engine temperature (ϑ_{eng}) or jumping to another location in the same lookup table or both.

[0085] This allows for instantaneous switching between corrections, which themselves have been found by controllers with a sufficiently low bandwidth.

[0086] Figure 8 shows a second embodiment of a torque controller disposed in the feedback path shown in Figure 4.

[0087] As mentioned above, it is preferred to schedule the torque controller in a similar way as the at least one lookup table used for conversion of $T_{ind,setpt}$ within the feedforward path. If a one-step conversion is carried out within the feedforward, in which torque setpoint $T_{ind,setpt}$ is converted to injection pulse duration (t_{pulse}) in only one-step, a controller setup can be used as shown in Figure 8. The output signal or output data of such a controller is the correction (Δt_{pulse}) of injection duration $(t_{pulse})\cdot$ For more details the reader is referred to the explanations given with respect to Figure 7.

[0088] Figure 9 shows an embodiment of a torque controller disposed in the feedback path and used during mode change for diesel particulate filter regeneration.

[0089] For transition to diesel particulate filter regeneration mode intake manifold pressure p_i and additional fuel mass $w_{f,post}$ injected during at least one post injection are used as scheduling variables, i.e., for scheduling the at least one lookup table beside engine speed N and torque setpoint $T_{ind,setpt}$. Hence, the lookup table used is a four-dimensional one

[0090] This controller setup could be compared with the controllers shown in Figure 7 and 8. The difference is that a specific engine operating point op_i is characterised by intake manifold pressure p_i and additional fuel mass $w_{f,post}$ injected instead of engine temprature (ϑ_{eng}). The lookup tables shown in Figure 9 are switched or interpolated based on intake manifold pressure p_i and additional fuel mass $w_{f,post}$, in order to generate the output data (Δw_f), i.e., the correction of the manipulated variable, namely fuel mass (w_f).

[0091] Figure 10 shows schematically an 1-controller, characterised by controller parameters K_I, used as torque controller disposed in the feedback path.

[0092] Figure 11 shows schematically a PI-controller, characterised by controller parameters K_P and K_I, used as torque controller disposed in the feedback path, which is characterised by controller parameters K_P and K_I

[0093] For these controllers, only the integrator variable constitutes the controller state which needs to be scheduled, whereas the P-part adapts instantaneously to new operating conditions and thus does not need to be scheduled. The controller parameters (K_P, K_I) can be scheduled if the bandwidth b of the controllers needs to be operating point dependent.

[0094] Both torque controller use the deviation ΔT_{ind} between setpoint $T_{ind,setpt}$ and actual value T_{ind} for the indicated torque to adapt a lookup table and the engine speed N, torque setpoint $T_{ind,setpt}$ and engine temperature (ϑ_{eng}) as input data for reading out from said lookup table the correction (Δw_f) of the manipulated variable (w_f) as output data.

Reference signs

[0095]

α_{ped}	accelerator pedal position
ϑ_{eng}	engine temperature
b	bandwidth
DPF	diesel particulate filter
ECU	engine control unit
EGR	exhaust gas recirculation
fi	frequency of a harmonic
K_1	parameter of a discrete-time integrating controller
K_P	parameter of a proportional controller part
LNT	lean NO_x trap
m	number of different engine modes
n	number of indexing parameters
n_{cyl}	number of cylinders
N	engine speed
op_i	specific engine operating point
p	in-cylinder pressure
P_{fuel}	fuel pressure
p_i	intake manifold pressure
t_i	intake air temperature
t_{pulse}	injection duration
Δt_{pulse}	correction of injection duration
T	torque demand
T_{ind}	actual value T_{ind} of torque
ΔT_{ind}	deviation between setpoint $T_{ind,setpt}$ and actual value T_{ind} of indicated torque
$T_{clutch,setpt}$	torque at the clutch
$T_{ind,setpt}$	indicated torque demand
VVT	variable valve timing
w_f	fuel quantity, fuel mass or fuel volume
Δw_f	correction of fuel mass
$w_{f,post}$	post injection quantity

x indexing parameters, input data

Claims

1. A method of controlling indicated torque for internal combustion engines by means of feedback control, wherein

   - the torque setpoint $T_{ind,setpt}$ is computed from the accelerator pedal position (α_{ped}), the torque losses and, if necessary, additional signals like engine speed, gear and the like,
   - said torque setpoint $T_{ind,setpt}$ is converted into the injection pulse duration (t_{pulse}) within a feedforward path,
   - the in-cylinder pressure p created by burning the fuel injected during injection pulse duration (t_{pulse}) is measured and used for calculating actual indicated torque T_{ind},
   - said actual indicated torque T_{ind} is controlled to the setpoint $T_{ind,setpt}$ via feedback control, i.e., by closing the control loop by means of a feedback path, in order to adjust said actual indicated torque T_{ind},

   characterised in that

   - said feedback path is provided by a torque controller which uses, possibly in addition to other signals which describe the engine operating conditions, the deviation ΔT_{ind} between setpoint $T_{ind,setpt}$ and actual value T_{ind} for the indicated torque as an input for updating at least one lookup table storing the manipulated variable, i.e., the correction of said manipulated variable, which is used as output data to adjust said actual indicated torque T_{ind},,
   - said additional signals are used for scheduling said at least one lookup table in order to enable a fast controller reaction during transient conditions, when the engine operating conditions are changing such that the correction of the manipulated variable is read out from said at least one lookup table by using the scheduling parameters as input data, and
   - said torque controller is provided with a low bandwidth b due to noise on the measured in-cylinder pressure signal, p, and thus on the calculated torque, T_{ind}, in order to make said manipulated variable less sensitive to the noise of T_{ind} by slowing down the convergence of the actual value T_{ind} for the indicated torque to the setpoint $T_{ind,setpt}$, if deviation ΔT_{ind} is affected substantially by signal noise.

2. A method according to claim 1, **characterised in that** said bandwidth b is lower than each of the frequencies f_i with large magnitude in the spectrum of the calculated, i.e., measured indicated torque T_{ind}, such that the relation between the bandwidth b and the frequencies f_i is described by the following expression: $b < f_i$.

3. A method according to any of the preceding claims, **characterised in that** said scheduling variables describing the engine operation conditions comprise engine speed N, load $T_{ind,setpt}$ and/or engine temperature (ϑ_{eng}).

4. A method according to any of the preceding claims, **characterised in that** a PI-controller is used as torque controller, which is **characterised by** controller parameters K_P and K_I.

5. A method according to any of the claims 1 to 3, **characterised in that** an 1-controller is used as torque controller, which is **characterised by** controller parameters K_I.

6. A method according to claim 4 or 5, **characterised in that** only the integrator variable is scheduled.

7. A method according to claim 4, 5 or 6, **characterised in that** at least one of the controller parameters K_P and/or K_I is scheduled.

8. A method according to any of the preceding claims, **characterised in that** said conversion from torque setpoint $T_{ind,setpt}$ to injection pulse duration (t_{pulse}) is a two-step conversion.

9. A method according to claim 8, **characterised in that** within the first step of said two-step conversion said torque setpoint $T_{ind,setpt}$ is converted to fuel quantity (w_f) and in the second step said fuel quantity (w_f) is converted to said injection pulse duration (t_{pulse}).

10. A method according to any of the claims 1 to 7, **characterised in that** said conversion from torque setpoint $T_{ind,setpt}$ to injection pulse duration (t_{pulse}) is a one-step conversion.

11. A method according to any of the preceding claims, **characterised in that** said at least one lookup table of said controller is scheduled in a similar way as the at least one lookup table used for conversion within the feedforward path., i.e., by using the same scheduling variables.

12. A method according to any of the preceding claims, **characterised in that** said at least one lookup table of said controller is stored in a permanent memory unit.

13. A method according to any of the preceding claims, **characterised in that** for controlling torque during a specific engine mode, said engine mode is used as an additional scheduling variable for said at least one lookup table.

14. A method according to any of the preceding claims, **characterised in that** for controlling torque during a specific engine mode, a specific set of at least one lookup table assigned to said engine mode is used.

15. A method according to any of the preceding claims, **characterised in that** for controlling torque during a transition between different engine modes, said specific transition is used as an additional scheduling variable for said at least one lookup table.

16. A method according to any of the preceding claims, **characterised in that** for controlling torque during a transition between different engine modes, a specific set of at least one lookup table assigned to said specific transitions is used.

17. A method according to any of the preceding claims, **characterised in that** for controlling torque during a transition between different engine modes said manipulated variable, i.e., the correction of the manipulated variable, is found by interpolation using the lookup tables of said different engine modes.

18. A method according to any of the claims 14 to 17, **characterised in that** for controlling torque during a transition between different engine modes or during a specific engine mode, said at least one lookup table is scheduled on variables, i.e., parameters, describing said transition or said specific engine mode.

19. A method according to claim 18, **characterised in that** said variables used for scheduling said at least one lookup table are changing more slowly during engine mode transitions than the manipulated variable, i.e., the correction of the manipulated variable.

20. A method according to any of the claims 15 to 19, **characterised in that** during the transition to and/or from diesel particulate filter regeneration, mode intake manifold pressure p_i and additional fuel mass $w_{f,post}$ injected during at least one post injection are used as scheduling variables, i.e., for scheduling the at least one lookup table.

21. A method according to any of the claims 15 to 19, **characterised in that** during transition from normal, lean operation to rich operation for purging a LNT and/or back, said at least one lookup table is scheduled on EGR level or mass air flow, intake manifold pressure p_i, and/or post-injection fuel quantity $w_{f,post}$.

22. A method according to any of the claims 15 to 19, **characterised in that** during transition to and/or from HCCI-mode, said at least one lookup table is scheduled on EGR level and intake air temperature t_i.

Amended claims in accordance with Rule 86(2) EPC.

1. A method of controlling indicated torque for internal combustion engines by means of feedback control, wherein

■ the torque setpoint $T_{ind,setpt}$ is computed from the accelerator pedal position (α_{ped}), the torque losses and, if necessary, additional signals like engine speed, gear and the like,
■ said torque setpoint $T_{ind,setpt}$ is converted into the injection pulse duration (t_{pulse}) within a feedforward path,
■ the in-cylinder pressure p created by burning the fuel injected during injection pulse duration (t_{pulse}) is measured and used for calculating actual indicated torque T_{ind},
■ said actual indicated torque T_{ind} is controlled to the setpoint $\mathrm{T_{ind,setpt}}$ via feedback control, i.e., by closing the control loop by means of a feedback path, in order to adjust said actual indicated torque $\mathrm{T_{ind}}$,

characterised in that

■ said feedback path is provided by a torque controller which uses, possibly in addition to other signals which describe the engine operating conditions, the deviation ΔT_{ind} between setpoint $T_{ind,setpt}$ and actual value T_{ind} for the indicated torque as an input for updating at least one lookup table storing the correction of said manipulated variable, which is used as output data to adjust said actual indicated torque T_{ind},
■ said other signals are used for scheduling said at least one lookup table in order to enable a fast controller reaction during transient conditions, when the engine operating conditions are changing such that the correction of the manipulated variable is read out from said at least one lookup table by using the scheduling parameters as input data, and
■ said torque controller is provided with a low bandwidth b due to noise on the measured in-cylinder pressure signal, p, and thus on the calculated torque, T_{ind}, in order to make said manipulated variable less sensitive to the noise of T_{ind} by slowing down the convergence of the actual value T_{ind} for the indicated torque to the setpoint $T_{ind,setpt}$, if deviation ΔT_{ind} is affected substantially by signal noise.

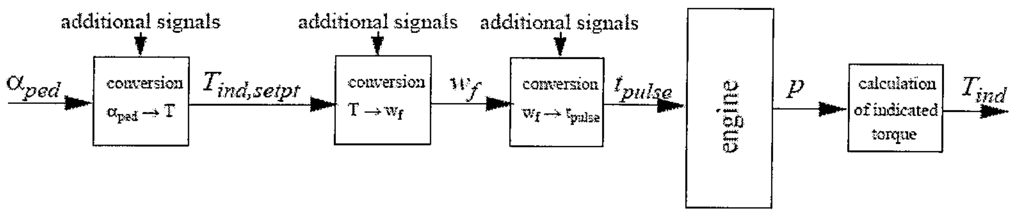


Fig. 1

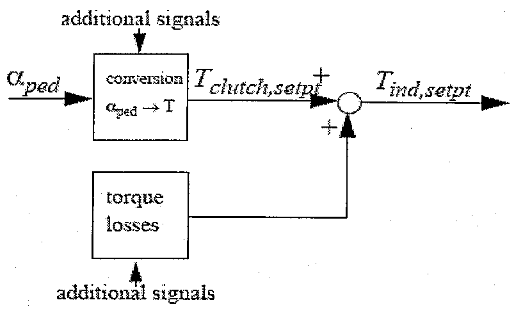


Fig. 2

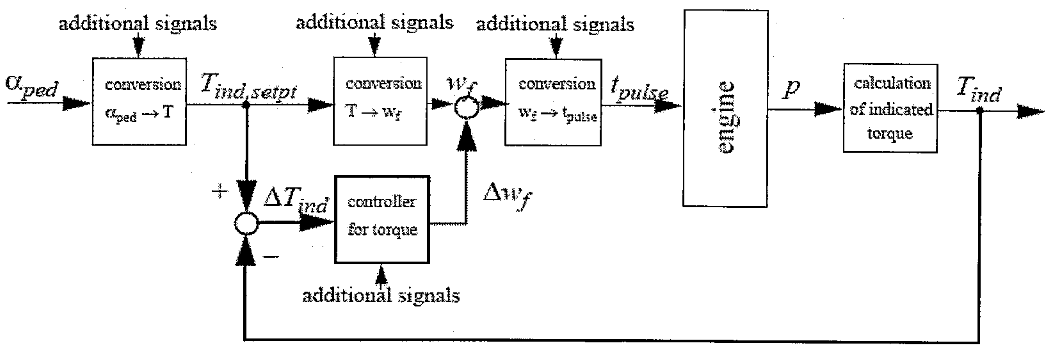


Fig. 3

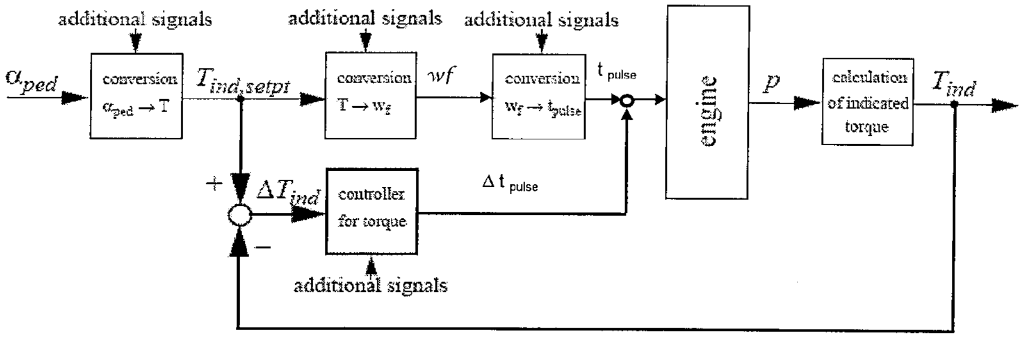


Fig. 4

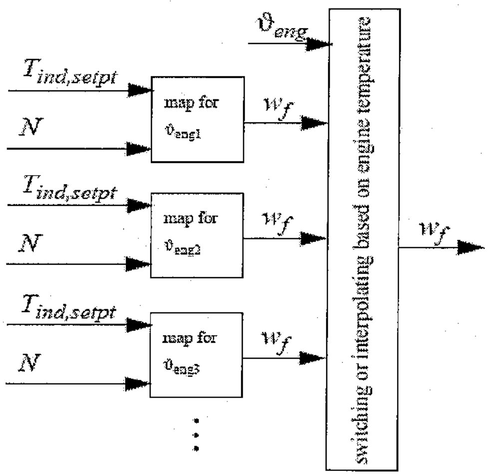


Fig. 5

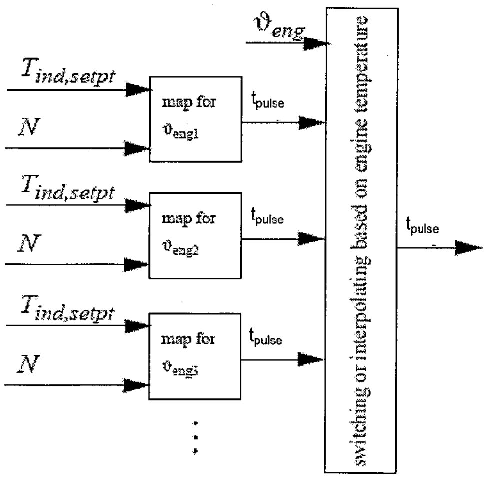
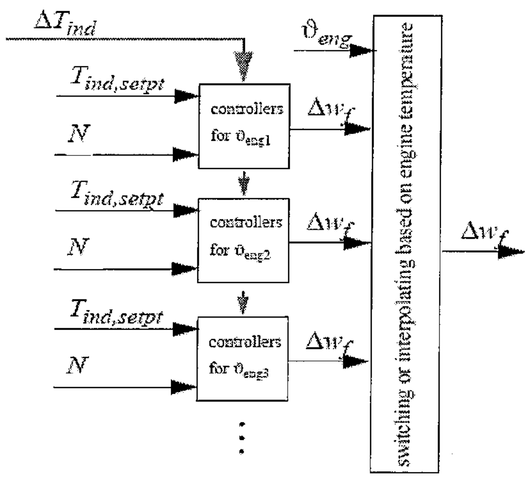
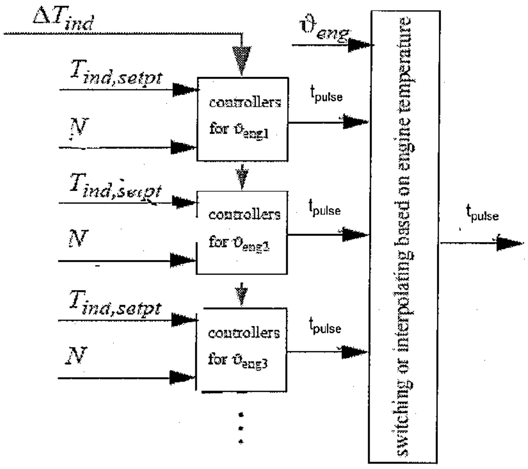


Fig. 6



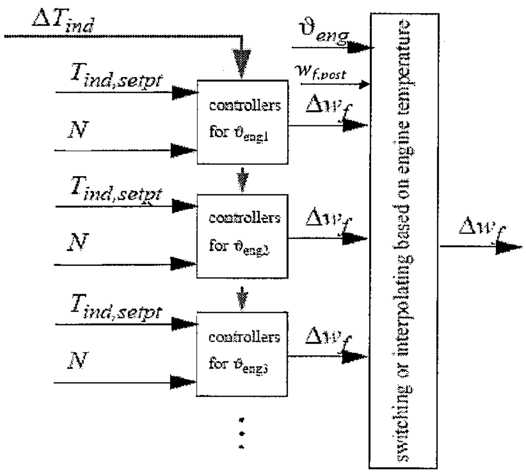
ΔT_{ind}
ϑ_{eng}
$T_{ind,setpt}$
N
controllers for ϑ_{eng1}
Δw_f
controllers for ϑ_{eng2}
controllers for ϑ_{eng3}
switching or interpolating based on engine temperature

Fig. 7



ΔT_{ind}
ϑ_{eng}
$T_{ind,setpt}$
N
controllers for ϑ_{eng1}
t_{pulse}
controllers for ϑ_{eng2}
controllers for ϑ_{eng3}
switching or interpolating based on engine temperature

Fig . 8



ΔT_{ind}
ϑ_{eng}
$w_{f,post}$
$T_{ind,setpt}$
N
controllers for ϑ_{eng1}
Δw_f
controllers for ϑ_{eng2}
controllers for ϑ_{eng3}
switching or interpolating based on engine temperature

Fig. 9

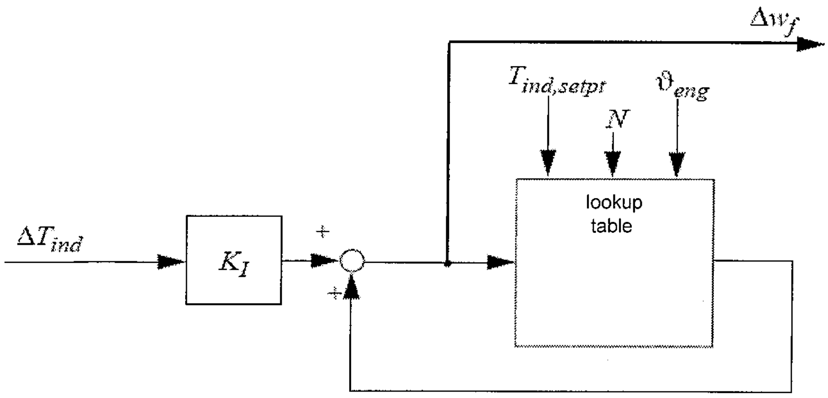


Fig. 10

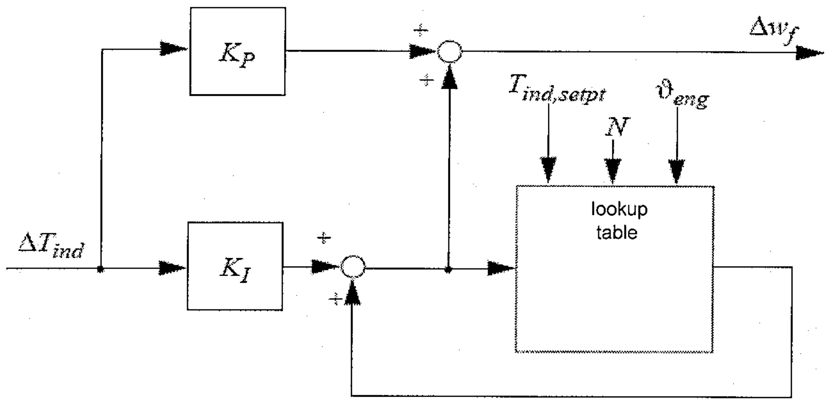


Fig. 11

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 05 10 2982

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
D,A	GB 2 331 154 A (* ROBERT BOSCH GMBH) 12 May 1999 (1999-05-12) * the whole document * -----	1-22	F02D41/14 F02D41/24 F02D35/02 F02D41/30
A	US 2002/162540 A1 (MATTHEWS GREGORY PAUL ET AL) 7 November 2002 (2002-11-07) * figures 1,2 * * paragraphs [0006], [0007] * * paragraphs [0015] - [0023] * -----	1-22	
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TECHNICAL FIELDS SEARCHED (Int.Cl.7)
F02D

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	31 August 2005	Parmentier, H

CATEGORY OF CITED DOCUMENTS

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31-08-2005

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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