Title: METHOD OF DETERMINING INJECTION PARAMETERS FOR AN INJECTOR

Abstract: A method of determining a minimum drive pulse (MDP) for an injector (7) in a fuel system (1) within an engine, the injector being associated with a fuel source (4), the method comprising: (a) measuring a first pressure in the fuel system; (b) sending (90) a drive pulse of a first length to the injector; (c) measuring a second pressure in the fuel system; (d) determining if an injection event has occurred by calculating the pressure difference between the first and second pressures and comparing to a threshold pressure difference; (e) repeating (a) to (d) with drive pulses of progressively increasing lengths until an injection event has occurred and setting the drive pulse length associated with the injection event as the MDP of the injector, wherein the fuel source is periodically pressurised.
METHOD OF DETERMINING INJECTION PARAMETERS FOR AN INJECTOR

Field of Invention

The present invention relates to a method of determining injection parameters for an injector. In particular, the present invention relates to a method and associated apparatus for determining the minimum drive pulse of an injector within a fuel injection system of an engine. The present invention further relates to methods of diagnosing injector and injection system faults.

Background to the Invention

There is a need in fuel injection equipment (FIE) to compensate for parts wearing over the lifetime of the product to ensure emissions and performance remains constant over life. One parameter that may vary over the lifetime of a fuel injector is the minimum drive pulse (MDP). A drive pulse relates to a drive signal applied to an injector via injector drive circuitry by an electronic control unit (ECU). The minimum drive pulse corresponds to the shortest drive signal that can be applied to an injector to initiate injection.

One known method of Minimum Drive Pulse detection (MDP) in an FIE control system comprises monitoring a crankshaft speed within an engine system. In this method, the minimum duration of FIE injection time that induces a fuel quantity to be injected into the cylinder, is determined by monitoring crankshaft speed and detecting the moment at which sufficient fuel is injected such that a torque producing combustion event is produced. This method comprises disabling one cylinder out of a total of \( n \) number of cylinders and slowly increasing the injection time (i.e. slowly increasing the length of the drive pulse applied to the disabled cylinder/injector) on that disabled cylinder until the MDP is detected.

Although this method can accurately determine injector MDP values it has the disadvantage that it is intrusive to normal engine operation because it involves injecting fuel into the engine system which results in a combustion event. This method is therefore noticeable in terms of torque and noise variations while the test is being carried out. Additionally this method is only able to measure MDP at a limited reservoir pressure (i.e. when the engine is idling). If the reservoir pressure was, for example increased when the
engine was idling then this would increase engine noise and make combustion less efficient (i.e. it would result in poor emissions performance).

It is therefore an object of the present invention to provide a method of determining the minimum drive pulse of an injector in an injection system that substantially mitigates or overcomes the above mentioned problems.

**Statements of Invention**

According to a first aspect of the present invention there is provided a method of determining a minimum drive pulse (MDP) for an injector in a fuel system within an engine, the injector being associated with a fuel source, the method comprising: (a) measuring a first pressure in the fuel system; (b) sending a drive pulse of a first length to the injector; (c) measuring a second pressure in the fuel system; (d) determining if an injection event has occurred by calculating the pressure difference between the first and second pressures and comparing to a threshold pressure difference; (e) repeating (a) to (d) with drive pulses of progressively increasing lengths until an injection event has occurred and setting the drive pulse length associated with the injection event as the MDP of the injector, wherein the fuel source is periodically pressurised.

The present invention provides a method of determining the minimum drive pulse of an injector without the need to measure the crankshaft speed of the engine. The present invention measures the pressure within the fuel reservoir or common rail (source of pressurised fuel/fuel source) of an engine and analyses this pressure when an injector under test is sent drive pulse signals. The length of the drive pulse signals can be progressively increased until an injection event is detected and the minimum drive pulse can then be set accordingly. Conveniently, the present invention may also be arranged to determine a normal rate of pressure leakage in the system and account for the natural pressure leakage when determining when injection events have occurred in order to make the method more accurate. The first pressure measurement may precede the drive pulse sent to the injector under test and the second pressure measurement may follow the drive pulse sent to the injector under test (e.g. a predetermined period of time after the drive pulse is sent to the injector).
It is noted in the following description that the terms “drive pulse”, “drive pulse signal” and "injector ON time" are regarded as interchangeable and the length of a drive pulse has a direct relationship with the injector ON time.

The advantage of the present invention is that it is unobtrusive and undetectable in the driveline since the test can be performed when the vehicle is in a “foot off pedal” or coasting condition. Additionally, the test drive pulses sent to the injector under test can be scheduled for periods of engine operation when injection of fuel into the engine cylinder associated with the test cylinder will not result in work output, e.g. during an exhaust stroke of an engine.

As noted above the pressure within the fuel system may decay due to pressure leakage. The fuel source is therefore periodically pressurised (or re-pressurised) in order that the minimum drive pulse test may be performed at or near a desired pressure level. It is noted for example that at low fuel system pressures the minimum drive pulse length for an injector may be affected by fuel pressure variations. The ability to pressurise the fuel source periodically thereby enables a more accurate determination of the minimum drive pulse length to be made.

Conveniently the fuel source may be pressurised whenever the pressure within the fuel source falls below a predefined threshold. Alternatively, the fuel source may be pressurised every combustion cycle of the engine system. In a further alternative, the fuel source may be pressurised between step (d) and step (e).

In an engine system arrangement in which the fuel source is pressurised by a (or a plurality of) unit pump(s), there will be a plurality of pumping events per combustion cycle of the engine. In each pumping event a unit pump will deliver a metered dose of fuel to the fuel source (fuel reservoir) in order to pressurise the fuel source. In such an engine system arrangement steps (a) to (d) may be performed between two consecutive pumping events. In this way, the fuel source may be periodically pressurised by the action of the unit pump(s).

Steps (a) to (d) may also be repeated in accordance with step (e) between the two consecutive pumping events until an injection event has occurred.
Alternatively, a proportion of the plurality of pumping events each combustion cycle may be suspended and steps (a) to (d) may be performed when the pumping events are suspended. Suspending some of the regular pumping events allows more time for the minimum drive pulse test to be performed such that a more accurate determination of the minimum drive pulse may be made. Suspending some of the pumping events also allows a pressure leakage profile to be determined as described below.

Steps (a) to (d) may be repeated during the period that the pumping events are suspended until an injection event has occurred. Alternatively, following step (d) the drive pulse length may be increased and a further sequence of steps (a) to (d) may be performed in the subsequent combustion cycle of the engine. Furthermore, each further sequence of steps (a) to (d) may be performed in a different combustion cycle. In other words one set of steps (a) to (d) may be performed per combustion cycle of the engine and each repetition of steps (a) to (d) may be performed in a different combustion cycle.

A plurality of drive pulses of a given length may be sent to the injector in step (b). It is noted that in some circumstances it may be the case that the pressure sensor within the fuel system is not sufficiently sensitive to detect the pressure drop that accompanies an injection event. If this is the case then the method may be adapted slightly to perform a series of injections on the same injector during one crankshaft revolution. This may therefore result in a larger cumulative pressure drop in the fuel system which may be detected by the pressure sensor.

Conveniently, a pressure threshold may be set prior to step (a). In this manner the test may be performed at or around a desired test pressure. In such a case, the periodic pressurisation may be arranged to return the fuel source to the test pressure for the duration of the test.

The method may be performed when the fuel system is in a closed pressurised state. Such a closed pressurised state may be achieved either by closing all the injectors within the fuel system and ceasing pumping of fuel to the source or by scheduling the test to run during a portion of the engine cycle when the injectors are closed and the pump is not actively charging the fuel source. In this latter example, the pump may conveniently be set to compensate for natural fuel leakage.
Conveniently, the determining step may determine that an injection event has occurred if the absolute value (i.e. the modulus) of the pressure difference between the first and second pressure measurements exceeds a threshold pressure difference.

Preferably, the method may further comprise determining a pressure leakage profile for the injector such that an expected pressure drop due to fuel leakage between the first and second pressure measurements can be calculated. The determining step may then preferably calculate the pressure difference between the first and second pressures, subtract the expected pressure drop due to fuel leakage and compare the remainder to a threshold pressure difference in order to determine if an injection event has occurred. It is noted that by accounting for the natural leakage within the fuel system the determination of MDP for the injectors can be made more accurate.

The pressure leakage profile may conveniently be determined by sampling the pressure in the fuel system at a plurality of measurement points. The pressure leakage profile may be measured periodically or every combustion cycle. The profile may, however, only be measured once per MDP test in order to reduce the noise in the system during subsequent pressure measurements. It is noted that the pressure leakage profile may comprise a pressure versus time relationship and the method may conveniently further comprise determining the presence of a fault in the fuel system if the determined pressure leakage profile exceeds a predefined profile envelope.

The MDP value determined in step (e) may preferably be stored for use in engine operation. This MDP value may then be compared against a previously stored MDP value for the injector and the presence of an injector fault may be determined if the MDP value determined in step (e) deviates from the previously stored value by a predetermined amount. Additionally, or alternatively, the MDP value in step (e) may be compared against the MDP values of other injectors within the engine and the presence of an injector fault may be determined if the MDP value determined in step (e) deviates from the MDP values of the other injectors by a predetermined amount.

Preferably, steps (a) to (d) are repeated according to step (e) by progressively increasing the length of the drive pulse by a fixed amount, $\Delta a$.

Preferably, following the occurrence of an injection event, the method steps (a) to (e) are repeated for the same injector starting at the last drive pulse length not to cause an
injection event and wherein the fixed amount by which the drive pulse is increased in step (e) is changed to a second fixed amount, Ab, wherein $A_b < A_a$. It is noted that varying the injector ON time interval in this way can be used to speed the MDP test up (i.e. by performing interval searching). For example, an initial test could be performed at a relatively course resolution to ascertain the rough MDP value and then a further test (or tests) could be run (starting at the last step prior to injection in the previous, "coarser" version of the test) with a finer resolution to determine a more accurate value for the MDP.

Preferably, where the engine comprises a plurality of injectors, each injector may be tested in turn to determine the MDP of each injector.

According to a second aspect of the present invention there is provided an electronic control unit arranged to determine a minimum drive pulse (MDP) for an injector in a fuel system within an engine, the injector being associated with a fuel source, the electronic control unit being arranged to: (a) measure a first pressure in the fuel system; (b) send a drive pulse of a first length to the injector; (c) measure a second pressure in the fuel system; (d) determine if an injection event has occurred by calculating the pressure difference between the first and second pressures and comparing to a threshold pressure difference; (e) repeat (a) to (d) with drive pulses of progressively increasing lengths until an injection event has occurred, the electronic control unit being arranged to set the drive pulse length associated with the injection event as the MDP of the injector wherein the electronic control unit is arranged to periodically pressurise the fuel source.

The invention extends to a carrier medium for carrying a computer readable code for controlling an electronic control unit to carry out the method of the first aspect of the invention.

Brief Description of the drawings

In order that the invention may be more readily understood, reference will now be made, by way of example, to the accompanying drawings in which:

Figure 1 shows a representation of a typical fuel system within an engine;
Figure 2 shows a minimum drive pulse test method in accordance with an embodiment of the present invention;

Figure 3 is a plot showing an example of pressure decay due to natural leakage versus pressure during an MDP test according to the present invention;

Figure 4 shows the relationship between rail pressure, the derivative of rail pressure with respect to time and the injection on time (TON) according to an embodiment of the present invention;

Figure 5 shows an engine system comprising two unit pumps;

Figure 6 shows the pumping events of the engine system of Figure 5 in accordance with a further embodiment of the present invention;

Figure 7 shows a minimum drive pulse test method in accordance with the further embodiment of the present invention;

Figure 8 shows a linear approximation of natural decay between injections;

Figure 9 shows an MDP test in accordance with embodiments of the present invention.

Detailed Description of the Invention

Figure 1 shows a representation of a fuel system 1 within an engine comprising a fuel tank 2, a controllable high pressure fuel pump 3, a common rail (fuel reservoir) 4, a rail pressure sensor 5, a pressure limiter 6, a plurality of injectors 7 and an electronic control unit (ECU) 8.

In use the ECU 8 controls pumping of fuel from the tank 2 to the rail 4 by the pump 3. The ECU 8 also controls the operation of the injectors 7 and receives sensor data on the pressure within the rail 4 from the pressure sensor 5.

Figure 2 is a flow chart showing a minimum drive pulse test in accordance with an embodiment of the present invention. In Step 10 the ECU (Electronic Control Unit 8) determines that the vehicle is operating in a foot-off condition.
In Step 20 the ECU 8 initiates the MDP test and ceases all injections through the
injectors 7 within the fuel system 1. At the same time the ECU instructs a fuel pump 3 to
pressurise the fuel reservoir 4 to a predetermined pressure (PRES).

In Step 30 the ECU 8 checks via the pressure sensor 5 whether the test pressure \( P_{RES} \) has been achieved.

If the test pressure \( P_{RES} \) has not been achieved then in Step 40 the ECU waits for the
pressure in the reservoir 4 to increase. After a predetermined pause the ECU 8 then
returns to Step 30.

If the test pressure \( P_{RES} \) has been achieved then the ECU 8 moves to Step 50 in which
the ECU 8 then instructs the pump 3 to cease pumping. After reducing the pump fuelling
to zero output, the pressure in the fuel system 1 will begin to decay by natural leakage
(to the low pressure fuel tank 2). It is noted however that, with the exception of natural
fuel leakage, the fuel system 1 is now in a closed state since the injectors 7 are not being
operated and the fuel pump 3 is not supplying further fuel to the reservoir 4. The closed
nature of the fuel system 1 at this point allows the following process steps to be used to
determine injector MDP values.

It is noted that by reducing the fuel pump output to zero, the noise within the system is
reduced which aids in the diagnosis process.

The MDP test may be carried out at a variety of pressures and the ECU 8 may, for a
given MDP test, select a particular pressure threshold \( P_{TEST} \) from a number of pressure
thresholds. In Step 60, therefore, the ECU checks, via the pressure sensor 5, to see
whether the pressure in the fuel system has dropped below the selected threshold value.
If the pressure is not below the required threshold then the ECU waits (in Step 70) for the
pressure to decay via the natural leakage process mentioned above. If the pressure in
the fuel system is at the required level then the ECU moves to Step 80.

In Step 80, the natural leakage characteristic of the fuel system is determined by taking
two or more measurements of the reservoir pressure. From these measured pressure
values a pressure leakage versus time function can be determined. In a preferred
embodiment the leakage characteristic is approximated as a linear relationship to reduce processing requirements on the ECU.

As described below, if the ECU does not find that an injection event has occurred it may increase the injector on time and repeat the MDP test. It is however noted that once the natural leakage function has been determined in Step 80 then the method according to the present invention may subsequently skip Step 80 in any further repetition of the test. This is because the leakage profile detection step may introduce noise into the fuel system and so skipping Step 80 once the leakage function has been determined may help reduce noise during the MDP test and increase the accuracy of the result.

In Step 90, the reservoir pressure is measured \( P^0 \) is measured.

In Step 100, the ECU sends a drive pulse of duration \( T_{ON} \) to an injector. It is noted that in order to avoid the problems associated with the prior art the ECU sends the drive pulse at a point in the engine cycle that will not result in work output (e.g. during an exhaust stroke).

In Step 110, the reservoir pressure is again measured \( P_2 \).

In Step 120 the ECU may calculate the absolute difference between \( P_1 \) and \( P_2 \) and then subtract an expected pressure drop due to natural leakage (calculated from the leakage function determined in Step 80. The remainder of this calculation (the resultant pressure difference) may then be compared to a threshold value. If the remainder exceeds the threshold then the ECU may determine there has been an injection event. For example, for a typical engine system this difference threshold could be of the order of 1 to 10 Bar. Depending on the engine system however a significant change in pressure could be outside of this range.

If the ECU determines that the resultant pressure difference has not exceeded a predetermined threshold value (and that consequently an injection event has not occurred) then in Step 130 it increases the injector \( O \)N time \( (T_{ON}) \) by a predetermined increment and returns to Step 80.

In this way the ECU runs the MDP test with progressively increasing injector \( O \)N times until a significant change in pressure is detected in Step 120.
Once a significant change in pressure has been determined (i.e. the predetermined threshold pressure has been exceeded) then the length of the drive pulse that corresponds to the value of TON that resulted in that change is set, in Step 140, as the minimum drive pulse for that injector. This value is stored by the ECU for use in engine operation. Following Step 140 the reservoir 4 may be re-pressurised above PRES such that the MDP test can be run again for a further injector within the engine.

The above process steps can then be repeated for each injector within the engine system.

It is noted that an additional simple diagnostic test could be performed during Step 80 of the above process, i.e. before drive pulses are sent to the injector to determine a minimum drive pulse. If, at Step 80 during the process of determining the pressure leakage profile, the ECU measures a pressure drop, the magnitude of which exceeds a stored value, then a component failure within the fuel system could be determined. This "component failure indicator pressure drop" value could be pre-loaded into the ECU during manufacture/installation or could be uploaded during servicing.

A further diagnostic test could be performed after Step 140 in which the MDP value determined in Step 140 is compared to one or more previous MDP values for the injector under test. If the test result as determined in Step 140 has a drive pulse length that is significantly longer or shorter than the previous value then an injector failure may be determined. The permitted variation in MDP values between tests may be set as a parameter during ECU installation or during servicing etc.

A variation to the above further diagnostic test could be to compare the derived MDP value for the injector under test to the MDP values of the other injectors within the engine. If there is a significant difference between these values then an injector fault for the injector under test can be returned.

If the increments by which the injector ON time is increased in Step 130 are not small enough to provide adequate resolution then the test can be repeated starting at the step prior to MDP detection. In other words if the increment is 100 µs and no injection was determined at an TON time of 600 µs but injection was determined at 700 µs then the test
could be re-run with the initial TON time being set equal to 600 µs and the increment set
equal to 10µs.

It is also noted varying the injector ON time interval in this way can also be used to
speed the MDP test up (i.e. by performing interval searching). For example, an initial test
could be performed at a relatively coarse resolution to ascertain the rough MDP value
and then a further test (or tests) could be run (starting at the last step prior to injection in
the previous, "coarser" version of the test) with a finer resolution to determine a more
accurate value for the MDP.

It is also noted that the _PTEST_ threshold in Step 60 may be changed by the ECU so that
an MDP versus pressure profile may be determined for each injector. This enables a far
more accurate representation of the injector operation to be determined compared to the
prior art in which measurements were only ever taken at a single reservoir pressure.

Figure 3 shows a plot of pressure versus time for a fuel system operated in accordance
with the above process. Trace 200 shows how pressure decays within a closed fuel
system due to natural leakage. Trace 210 shows how the pressure varies during an MDP
test in accordance with an embodiment of the present invention. It can be seen that
Trace 210 comprises a number of "steps" 220 corresponding to injection events within
the engine.

Figure 4 combines a series of different figures together. The top figure shows how rail
pressure varies over time (for before and during a test). The middle figure shows a
corresponding plot of the rate of change of pressure over time. Finally, the bottom figure
shows the activation time (injector ON times) for the injector under test.

Figure 4 is also divided into three time periods. During period 1 the rail pressure is being
maintained, e.g. by the fuel pump, at a constant pressure. Correspondingly the derivative
of the pressure with respect to time is equal to zero during this period. The injector ON
time is set to zero during this period.

Period 2 corresponds to the MDP test in accordance with Figure 2 being run. It can be
seen that drive pulses of increasing length are being applied. At the same time the fuel
system has been set to a closed pressurised state and the pressure in the system is
slowly decaying as a result of natural leakage. The derivative (with respect to time) of the pressure shows a constant negative value.

At the start of period 3 the injector ON time equals or exceeds the minimum drive pulse length for the injector under test and the pressure within the system falls at a faster rate. This can be seen by the change in gradient of the top figure which is also reflected in the change in the pressure derivative (which has moved to a second, more negative value compared to period 2).

The injector ON time at the start of period 3 can therefore be used to set the minimum drive pulse for the injector under test.

Figure 5 shows a unit pump engine system comprising six injectors (7), in fluid communication with a fuel reservoir (4) and two unit pumps (302, 304) for pumping fuel to the reservoir. Although two unit pumps are depicted in Figure 5 it is noted that there may be up to six pumps (i.e. an equal pump to injector ratio) within such a system. However, typically there would be two or three such pumps. In use, the pumps are arranged to deliver fuel to the reservoir in sync with injection events. In the case of a six unit pump arrangement therefore each unit pump would deliver at least one pumping event per combustion cycle of the engine (A "combustion cycle of the engine" is a complete engine cycle comprising two crankshaft revolutions (for a four stroke engine)). For the two unit pump arrangement depicted each unit pump would deliver three pumping events per combustion cycle of the engine.

Figures 6 and 7 detail a minimum drive pulse test in accordance with a further embodiment of the present invention.

Figure 6 shows the pumping events that occur during any given combustion cycle. Each scheduled pumping event (1, 2, 3, 4, 5 and 6) is depicted by the vertical dividers. The far left and far right vertical dividers both relate to pumping event number 4 indicating that Figure 6 "wraps around" from right to left.

The pressure within the reservoir is depicted underneath the pumping events and in the present example pressure was sampled every 120 degrees of crank angle. In order to allow a more accurate determination of the minimum drive pulse in accordance with the further embodiment of the present invention, a number of pumping events have been
disabled. Specifically, the unit pumps have been suspended such that pumping events 4, 5 and 6 do not occur.

The minimum drive pulse test is initiated at a predefined threshold pressure, \( P_{\text{TEST}} \). The start of the test in Figure 6 corresponds to the first suspended pumping event (pumping event 4). It can be seen that the rail/reservoir pressure decays from \( P_{\text{TEST}} \) due to natural decay within the fuel system thereby allowing a pressure leakage profile to be determined.

In the example of Figure 6 the pressure leakage profile is determined over 240 degrees of crank angle. At the point at which the sixth pumping event would normally occur a number of drive pulses of a given length are sent to one of the injectors within the fuel system. It is noted that each pulse is of the same length and, in the example of Figure 6, there are four such drive pulses.

Following the multiple drive pulses the pressure within the rail/reservoir is measured and compared to the rail/reservoir pressure before the drive pulses (taking into account the expected drop in pressure due to the natural leakage profile). In the event that the pressure difference (adjusted with the natural leakage value) exceeds a predetermined threshold then an injection event has occurred and will be noted thereby allowing the minimum drive pulse length to be set (or an upper limit for the minimum drive pulse length to be set).

As shown in Figure 6, half of the pumping events are disabled and half are enabled. During the "pumping enabled" or "re-pressurisation" portion of the combustion cycle it can be seen that the rail pressure is returned to the \( P_{\text{TEST}} \) threshold pressure.

Figure 6 shows half the pumping events disabled. However, in the event that the pumping events are not synchronous to the injection events, then pumping events could be completely disabled or alternatively all pumping events could be left in place. In these two variations then it is noted that \( P_{\text{res}} = P_{\text{Test}} \).

It is noted that the pressure increase after pumping event 2 is not the same as the increase after pumping event 3. The pressure increases after pumping events 2 & 3 are different as there are PID terms in the control (proportional-integral-derivative controller).
within the ECU causing the corrective pumping terms to be proportional to the error from
the desired pressure, i.e. more for pumping event 2 than pumping event 3.

Although Figure 6 depicts a step change in the rail pressure (thereby indicating that an
injection event has occurred) it is noted that no substantial change between the first and
second measured rail pressures may be observed. In such a case the pumping of the
unit pumps would be enabled to allow the test pressure within the rail to be achieved and
a further plurality of drive pulses (of slightly longer duration than those used in the current
combustion cycle) may be sent to the injector under test in the next combustion cycle.

This process may be repeated until an injection event occurs.

Figure 7 is a flow chart showing a minimum drive pulse test in accordance with the
further embodiment of the present invention (this further embodiment relates to the
arrangement of Figures 5 and 6 described above). It is noted that many of the process
steps are common to those of Figure 2 and for conciseness they have not been
described again. Differences to the process shown in Figure 2 are described below.

The minimum drive pulse test in accordance with the further embodiment proceeds
through steps 10 to 120 as before. In Figure 2, if the pressure difference between $P_1$ and
$P_2$ (taking into account the natural leakage expected) does not exceed a predetermined
threshold then the drive pulse length is increased in Step 130 and the process returns to
Step 80 (or Step 90 if Step 80 is skipped in further iterations of the test method). It can
therefore be seen that the pressure within the fuel system will decay in the Figure 2
embodiment until such time as the pressure difference exceeds the predetermined
threshold in Step 120.

In contrast, in the further embodiment of Figure 7 if the pressure difference between $P_1$
and $P_2$ (taking into account the natural leakage expected) does not exceed a
predetermined threshold then the drive pulse length is increased and the process returns
to Step 20. In Step 20 the unit pumps are enabled to pressurise the reservoir to or above
$P_{RES}$ (Step 30). The test then proceeds through Steps 30 to 120 again until such time as
a step change is detected in Step 120.

Figure 8 shows a representation of a pressure decay profile in which the leakage
function has been approximated as a linear relationship over time. Three sample
pressure points 250, 260, 270 (corresponding to the pressure measurements made in
Step 80 above) are shown. An injection event 280 is also shown and it can be seen that there is a noticeable pressure drop 290 from the extrapolated linear pressure leakage function. Such a pressure drop would be detected by the ECU (in Step 120 above) and would be indicative of an injection event occurring.

In certain circumstances it may be the case that the pressure sensor within the fuel system is not sufficiently sensitive to detect the pressure drop shown in Figure 8 above. If this is the case then the method may be adapted slightly to perform a series of injections 280, 282, 284 (at Step 90 of Figure 2/7) on the same injector during one crankshaft revolution. This would therefore result in a larger cumulative pressure drop 286 in the fuel system which may be detected by the pressure sensor.

This "multiple" injection variation is shown in Figure 9 in which three injection events (280, 282, 284) are shown. The pressure drop 286 due to these multiple injections is noticeably larger than the pressure drop 290 in Figure 8 and is now sufficiently large that the pressure sensor 5 can register the change.

It is noted that if the "multiple injection" variation of Figure 9 embodiment is used then the activation pulse durations sent to the injector under test should be of a consistent duration. It is also noted that the multiple injection variant is shown/used in Figure 6.

It will be understood that the embodiments described above are given by way of example only and are not intended to limit the invention, the scope of which is defined in the appended claims. It will also be understood that the embodiments described may be used individually or in combination.
CLAIMS

1. A method of determining a minimum drive pulse (MDP) for an injector (7) in a fuel system (1) within an engine, the injector being associated with a fuel source (4), the method comprising:
   a) measuring a first pressure in the fuel system;
   b) sending (90) a drive pulse of a first length to the injector;
   c) measuring a second pressure in the fuel system;
   d) determining if an injection event has occurred by calculating the pressure difference between the first and second pressures and comparing to a threshold pressure difference;
   e) repeating (a) to (d) with drive pulses of progressively increasing lengths until an injection event has occurred and setting the drive pulse length associated with the injection event as the MDP of the injector

   wherein the fuel source is periodically pressurised.

2. A method as claimed in Claim 1, wherein the fuel source is pressurised whenever the pressure within the fuel source falls below a predefined threshold.

3. A method as claimed in Claim 1, wherein the fuel source is pressurised every combustion cycle of the engine system.

4. A method as claimed in Claim 1, wherein the fuel source is pressurised between step (d) and step (e).

5. A method as claimed in any preceding claim, wherein the engine comprises a unit pump for pumping fuel to the fuel source in a plurality of pumping events per combustion cycle of the engine.

6. A method as claimed in Claim 5, wherein steps (a) to (d) are performed between two consecutive pumping events.

7. A method as claimed in Claim 6, wherein steps (a) to (d) are repeated between the two consecutive pumping events until an injection event has occurred.
8. A method as claimed in Claim 5, further comprising suspending a proportion of the plurality of pumping events each combustion cycle and wherein steps (a) to (d) are performed when the pumping events are suspended.

9. A method as claimed in Claim 8, wherein steps (a) to (d) are repeated during the period that the pumping events are suspended until an injection event has occurred.

10. A method as claimed in Claim 8, wherein, following step (d) the drive pulse length is increased and a further sequence of steps (a) to (d) is performed in the subsequent combustion cycle of the engine.

11. A method as claimed in Claim 10, wherein each further sequence of steps (a) to (d) is performed in a different combustion cycle.

12. A method as claimed in any preceding claim, wherein a plurality of drive pulses of a given length are sent to the injector in step (b).

13. A method as claimed in any preceding claim, further comprising setting a pressure threshold prior to step (a).

14. A method as claimed in Claim 1, wherein the method is performed when the fuel system is in a closed pressurised state.

15. A method as claimed in Claim 14, wherein the closed pressurised state is achieved by closing all injectors within the fuel system and ceasing pumping of fuel to the source of pressurised fuel (4).

16. A method as claimed in any preceding claim, wherein an injection event is determined to have occurred if the absolute value of the pressure difference between the first and second pressure measurements exceeds the threshold pressure difference.

17. A method as claimed in any preceding claim, further comprising determining a pressure leakage profile for the injector such that an expected pressure drop due to fuel leakage between the first and second pressure measurements can be calculated.
18. A method as claimed in Claim 17, wherein the step of determining if an injection event has occurred comprises calculating the pressure difference between the first and second pressures, subtracting the expected pressure drop due to fuel leakage and comparing the remainder to a threshold pressure difference,

19. A method as claimed in Claim 17 or 18, further comprising sampling (80) the pressure in the fuel system at a plurality of measurement points in order to determine the pressure leakage profile for the injector.

20. A method as claimed in any one of Claims 17 to Claim 19, wherein the pressure leakage profile comprises a pressure versus time relationship and the method further comprises determining the presence of a fault in the fuel system if the determined pressure leakage profile exceeds a predefined profile envelope.

21. A method as claimed in any preceding claim, wherein the MDP value determined in step (e) is stored for use in engine operation.

22. A method as claimed in Claim 21, wherein the MDP value in step (e) is compared against a previously stored MDP value for the injector and the presence of an injector fault is determined if the MDP value determined in step (e) deviates from the previously stored value by a predetermined amount.

23. A method as claimed in Claim 21 or Claim 22, wherein the MDP value in step (e) is compared against the MDP values of other injectors within the engine and the presence of an injector fault is determined if the MDP value determined in step (e) deviates from the MDP values of the other injectors by a predetermined amount.

24. A method as claimed in any preceding claim, wherein steps (a) to (d) are repeated according to step (e) by progressively increasing the length of the drive pulse by a fixed amount, Aa.

25. A method as claimed in Claim 24, wherein, following the occurrence of an injection event, the method steps (a) to (e) are repeated for the same injector starting at the last drive pulse length not to cause an injection event and wherein the fixed amount by which the drive pulse is increased in step (e) is changed to a second fixed amount, Ab, wherein $Ab < Aa$. 
26. A method as claimed in any preceding claim, wherein the engine comprises a plurality of injectors and each injector is tested in turn to determine the MDP of each injector.

27. A method as claimed in any preceding claim, wherein the first pressure measurement precedes the drive pulse sent to the injector and the second pressure measurement is made after the drive pulse has been sent to the injector.

28. A method as claimed in Claim 27, wherein the second pressure measurement is made at a given time.

29. An electronic control unit (8) arranged to determine a minimum drive pulse (MDP) for an injector (7) in a fuel system (1) within an engine, the injector being associated with a fuel source (4), the electronic control unit being arranged to:

a) measure a first pressure in the fuel system;

b) send a drive pulse of a first length to the injector (7);

c) measure a second pressure in the fuel system;

d) determine if an injection event has occurred by calculating the pressure difference between the first and second pressures and comparing to a threshold pressure difference

e) repeat (a) to (d) with drive pulses of progressively increasing lengths until an injection event has occurred, the electronic control unit being arranged to set the drive pulse length associated with the injection event as the MDP of the injector wherein the electronic control unit is arranged to periodically pressurise the fuel source.

30. A carrier medium for carrying a computer readable code for controlling an electronic control unit (8) to carry out the method of any one of Claims 1 to 28.
Vehicle in 'foot-off' motion.

Cease injecting and pressurise reservoir.

Pressure at or above $P_{RES}$?

YES

Cease pumping, allow reservoir to drain via leakage.

Pressure below $P_{TEST}$ threshold?

YES

Take 2 or more successive measurements of reservoir pressure. Determine linear function of leakage characteristic.

Measure reservoir pressure $P_1$.

Perform series of $N_{ON}$ injections at duration $T_{ON}$.

Measure reservoir pressure $P_2$.

YES

$|P_1 - P_2|$ - natural leakage drop > predetermined threshold?

Calculate MDP from $T_{ON}$.

NO

Increase $T_{ON}$.

Pause

FIGURE 2
FIGURE 4
FIGURE 6

Rail Pressure sampled every 120°CA

Pumping Disabled

Re-pressurisation

Natural decay

Pressure drop due to multi-injections

Pumping

pressure measurements

Natural decay
Vehicle in 'foot-off' motion.

Cease injecting and pressurise reservoir.

Pressure at or above $P_{RES}$?

YES

Cease pumping, allow reservoir to drain via leakage.

Pressure below $P_{TEST}$ threshold?

YES

Take 2 or more successive measurements of reservoir pressure. Determine linear function of leakage characteristic.

Measure reservoir pressure $P_1$.

Perform series of $N_{INU}$ injections at duration $T_{ON}$.

Measure reservoir pressure $P_2$.

$|P_1 - P_2|$ - natural leakage drop > predetermined threshold?

YES

Calculate MDP from $T_{ON}$.

Pause

Pause

Increase $T_{ON}$
FIGURE 9
A. CLASSIFICATION OF SUBJECT MATTER
INV. F02D41/38 F02D41/24

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

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
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<td>Y</td>
<td>EP 0 748 930 A2 (DAIMLER BENZ AG [DE] DAIMLER CHRYSLER AG [DE]) 18 December 1996 (1996-12-18) abstract; figures 2,3 column 3, line 10 - column 3, line 54</td>
<td>1-17, 19-26, 29,30</td>
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X Further documents are listed in the continuation of Box C.  X See patent family annex.

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Date of the actual completion of the international search
2 February 2012

Date of mailing of the international search report
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