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(54) **Method of controlling an electromagnetic actuator**

(57) A method of controlling an electromagnetic actuator having an excitation coil and a movable armature is presented. An actuating event is triggered by applying a control signal to move said armature from a rest position thereof towards an actuating position. The method comprising the steps of:
determining a switch-off time (t_{off}) at which the armature returns to its rest position;
determining a time (t_{max}) at which the armature reaches an extremum of its stroke during the actuation event;
computing a switch-on time on the assumption that the switch-on time (t_{on}) is separated from the switch-off time by an actuating duration (t_{act}), which represents approximately twice the time separating the extremum stroke time (t_{max}) from the switch-off time (t_{off}).

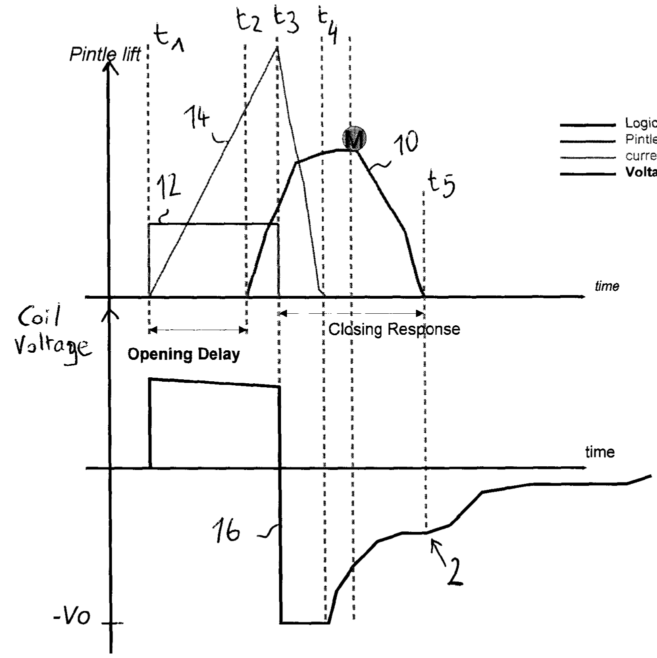

FIG. 1

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Description

FIELD OF THE INVENTION

[0001] The present invention generally relates to electromagnetic actuators and more specifically to a method of controlling an electromagnetic actuator taking into account switching delays. A particular field of application is that of internal combustion engines using electromagnetically actuated fuel injectors.

BACKGROUND OF THE INVENTION

[0002] The contemporary design of spark ignited internal combustion engines must cope with the increasingly stringent regulations on pollutant emission. Accordingly, automotive engineers strive for designing engines with low fuel consumption and low emission of pollutants, which implies including electronic devices capable of monitoring the combustion performance and emissions in the exhaust gases.

[0003] The issue of fuel economy has been addressed *i.a.* by varying the injection schemes. Currently, direct injection engines and in particular gasoline stratified charge engines are considered to be very efficient in terms of fuel economy.

[0004] One requirement to reduce emissions from a spark ignited internal combustion engine is an accurate control of the combustion air/fuel ratio. This is usually done by metering a precisely controlled amount of fuel based on a measured or inferred air charge mass inducted into the engine; many control schemes are known in the art to control the air/fuel ratio. It is e.g. customary to install an oxygen sensor in the engine exhaust line and to use the sensor output as a feedback signal for closed loop fuel control.

[0005] Another parameter known for affecting the injected fuel quantity is the response time of the injector, due to the response of the electromagnetic actuators. Indeed, conventionally with electromagnetic actuators a certain time period elapses between the application of the command signal and the moment the actuator actually starts moving; or between the moment the command signal ends and the injector actually reaches its closed position. The knowledge of the response times (or response delays) at switch-on and switch-off thus allows for a more precise control of the actuator. WO 03/023211, e.g., describes a method of determining response times of electromagnetic devices. The determination of injector response times at switch-on and switch-off is based on current detection; the determination of the response time at closing is also described based on voltage detection.

[0006] Deviation and variability between injectors are usually due to the dispersion of the injectors characteristics linked to the production process spread and/or to the time-drift variations of the same characteristics due to ageing. Thus, fuel injector flow variations need to be corrected.

[0007] The problem of fuel variability is particularly critical for low fuel injections, i.e. when injecting small or minute fuel amounts. In such case, the knowledge of the opening and closing delays is particularly useful to conduct an optimised injector control.

OBJECT OF THE INVENTION

[0008] The object of the present invention is to provide a method of controlling an electromagnetic actuator with an alternative determination of switch-on time.

[0009] This object is achieved by a method as claimed in claim 1.

SUMMARY OF THE INVENTION

[0010] The present invention relies in part on previous findings made by the present Applicant that the accuracy of low (or minute) fuel injections can indeed be improved by detecting more precisely than before response timings of the pintle lift event of the injector and that injector response time data such as closing time data and opening time data can serve to correct the injection pulse width that is used to inject a desired quantity of fuel in the combustion chamber.

[0011] According to the present invention, a method of controlling an electromagnetic actuator having an excitation coil and a movable armature is proposed, wherein an actuating event is triggered by applying a control signal to move said armature from a rest position thereof towards an actuating position, and in particular actuating events where the armature motion is in the ballistic domain. The method comprises the steps of:

determining a switch-off time t_{off} at which the armature returns to its rest position;

determining a time t_{max} at which the armature reaches an extremum of its stroke during said actuation event; and

computing a switch-on time on the assumption that the switch-on time (t_{on}) is separated from the switch-off time by an actuating duration (t_{act}), which represents approximately twice the time separating the extremum stroke time (t_{max}) from the switch-off time (t_{off}).

[0012] The control signal for a next actuation event of the electromagnetic actuator can thus be corrected, respectively elaborated, taking into account the switch-on time.

[0013] In practice, for a fuel injector featuring a solenoid actuator, the so-learned timing information allows elaborating learned correction values that can be advantageously used for the injection control and namely for low injection pulses. First, learned correction values may be elaborated in respect of the closing times (t_{off}) on the one hand, and second, learned correction values may be elaborated in respect of the opening times (t_{on}) on the other hand. Preferably, a corrected control signal is elaborated that takes into account both the opening and closing delays.

[0014] While the closing time will typically vary with the injected fuel quantity and closing times may be learned for various injected quantities of fuel, the opening time of a given injector is considered to be relatively constant and one value of opening time may be stored per injector. However, this value may vary with ageing, or some injectors may have a different behaviour. Therefore, the determination of opening time may be periodically determined.

[0015] The present method has been particularly developed for an optimised control of modern fuel injectors, where the opening and closing delays may substantially affect the injected fuel quantity for "minute or "low" fuel injections, if not properly taken into account. Such "minute or "low" fuel injections are injection pulses of low fuel quantities, which are achieved through brief injector pintle openings and where the pintle is mainly in a transitory position between the fully open position and the closed position. Performing such low fuel injections involves operating the injector in the "ballistic" domain, where closing and opening time correction has appeared to be particularly advantageous. For current injectors, injections of fuel masses of up to 5 or 6 mg involve operation in the ballistic domain.

[0016] The present method is of particular interest for the control of fuel injectors with electromagnetic actuators of the so-called decoupled type, i.e. where the armature is not rigidly linked to the pintle, and thus tend to have a ballistic behaviour.

[0017] In a preferred embodiment, the timing t_{max} is determined as the timing at which a curve representative of the logarithm of the voltage at the excitation coil during a predetermined observation window before the switch-off time intersects a straight line representative of the logarithm of the excitation coil voltage after the switch-off time. Here the natural (base e) logarithm may be used, or other base.

[0018] The observation window may start after the fall of the control signal for the respective actuating event, preferably when it has been determined that the coil current has become null.

[0019] These and other embodiments of the present invention are recited in the appended dependent claims 2 to 8.

[0020] According to another aspect, the invention concerns a method of controlling fuel injection in an internal combustion engine according to claim 9.

[0021] According to a further aspect, the invention concerns an internal combustion engine comprising at least one cylinder with at least one fuel injector as defined in claim 11, respectively 12. The fuel injector comprises a pintle actuated by an electromagnetic actuator having an excitation coil and a movable armature. An engine management system (EMS) is adapted to trigger an actuating event (injection event) of the fuel injector by applying a control signal to the latter so as to move the armature, respectively the pintle, from a rest position thereof towards an actuating position and cause a corresponding fuel injection. Typically, the control signal is generated to on the basis of a fuel command pulse width, conventionally mapped in function of the fuel amount to be injected.

[0022] The engine management system is further configured to:

determine a time (tmax) at which the armature reaches an extremum of its stroke during said actuation event;

compute a switch-on time on the assumption that the switch-on time (ton) is separated from the switch-off time by an actuating duration (tact), which represents approximately twice the time separating the extremum stroke time (tmax) from a previously determined switch-off time (toff) at which the armature returns to its rest position.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] The present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1: comprises a graph showing the actuation logic, pintle stroke and coil current vs. time, with the lower graph showing the voltage evolution during the same time period; and

FIG. 2: comprises the same upper graph as in Fig. 1, and the lower graph shows In(V) over the same time period.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

[0024] The present inventors have developed the present method when working on opening and closing delays of fuel injectors operating in the ballistic domain. The present invention will thus now be explained in detail with regard to an actuating event of a fuel injector. As it will however clearly appear to those skilled in the art, the invention can be used to optimize the operation of any type of electromagnetic actuator having an excitation coil (also called solenoid), i.e. having an inductance, and a movable armature operating in the ballistic domain.

[0025] Hence, with reference to fuel injectors the switch off time t_{off} may be called closing time/delay and the switch-on time t_{on} may be referred to as opening time/delay.

[0026] It may further be noted that in the present variant, the opening and closing times are both determined from voltage feedback from the injector, which results in a coherent data processing as the timings can then simply be determined from a single source of information.

[0027] According to the present method, the switch-on time is determined on the assumption that the switch-on time is separated from the switch-off time by an actuating duration, which represents approximately twice the time separating the extremum stroke time from the switch-off time.

[0028] In a preferred variant, the this method can be implemented as follows:

- determining a switch-off timing t_{off} at which the armature returns to its rest position;
- determining a timing t_{max} at which the armature reaches an extremum of its stroke during said actuation event;
- computing an actuating duration as $t_{act} = C•(t_{off} - t_{max})$, where C is a coefficient between 0.8 and 1.2;
- computing a switch-on delay as $t_{on} = t_{off} - t_{act}$.

1. Determining the closing time

[0029] The determination of an injector closing time is known in the art. In the present variant, the injector closing time, noted t_{off} and occuring at time t5, is preferably deduced from the coil voltage.

[0030] As already mentioned, the determination of the injector pintle closing response is preferably carried out based on the voltage feedback from the injector. The voltage may be measured across the injector coil terminals. When the injector armature hits the seat and stops, there is a visible and measurable change in the slope of the injector coil voltage (indicated by arrow 2 in Fig.1). One may take the derivative of the coil voltage and the local maximum (the signal is generally a negative quantity) of the derivative of the coil voltage happens to closely approximate the closing time $\mathbf{t}_{off}$.

[0031] The typical waveform of the pintle position and the corresponding voltage are shown on Fig.1.

[0032] The perturbation in the voltage can be traced back to a change in the velocity term of the flux linkage *I.dL/dx.dx/dt,* where *dx/dt* is the velocity of the armature, which is greatly reduced when the pintle closes. The measurements preferably take place after the command pulse has ended and the currents have gone to zero, leaving only eddy currents and trapped flux in the magnetic circuit. These conditions enable an easier sensing of the closing voltage signature.

[0033] Furthermore, it has been observed that fuel mass is primarily determined by the pulse width and the closing delay of the injector pintle, after the pulse width ends.

[0034] Thanks to the determination of the closing time, it is hence possible to adjust the pulse width to prevent flow variation from one injector to the others. Closing Time t_{off} is then an excellent indicator of fuel flow: part with higher closing time will deliver more fuel than one with shorter closing time.

2. Determining the maximum stroke

[0035] As for the closing time detection, the determination of the maximum stroke is also prerably done on the basis of coil voltage feedback. And the present approach is actually based on the fact that the armature position affects the coil inductance value.

[0036] For a solenoid actuated injector, the inductance L depends on 2 parameters: the current i and the gap between armature (i.e. moving body) and coil, this gap being indicated by *x* in the following equation.

[0037] So, the inductance derivative can be written in the form of a total differential:

$$dL = \frac{\partial L}{\partial x} dx + \frac{\partial L}{\partial i} di \qquad \text{(eq. 1)}$$

[0038] And the variation of coil inductance over time can be written as:

$$\frac{dL}{dt} = \frac{\partial L}{\partial x}\frac{dx}{dt} + \frac{\partial L}{\partial i}\frac{di}{dt} \qquad \text{(eq. 2)}$$

[0039] The determination of the maximum stroke thus involves monitoring the coil inductance to extract motion characteristics.

[0040] Turning to Fig.1, line 10 indicates the pintle stroke (pintle lift), line 12 the actuation logic (command signal or pulse width), line 14 the current in the injector coil and line 16 the voltage at the injector coil (lower graph).

[0041] The present example is that of an actuating event in the ballistic domain. As illustrated by line 12, the actuation logic generates a step between times t1 and t3 in order to charge the coil with the aim of opening the injector. The pintle starts moving at time t2 and closes at time t5.

[0042] From time t3 to t5, the goal is to close the actuator and the control logic applies directly after time t3 a negative voltage $-V_0$ to the coil in order to collapse the current in the coil and cancel the magnetic field.

[0043] After time t4, the current is null and the $-V_0$ voltage is suppressed. The coil voltage evolves from $-V_0$ to 0.

[0044] The current being null after time t4, *di/dt* is also null and equation 2 can be rewritten as:

$$\frac{dL}{dt} = \frac{\partial L}{\partial x}\frac{dx}{dt} \quad \text{(eq.3)}$$

[0045] This implies that after time t4, the variation of inductance is only due to the motion of the armature.

[0046] The equation of the voltage across the coil after time t4 then becomes that of a simple coil-resistance circuit, to which a voltage V_0 is applied until time t4. This can be written:

$$V_L(t) = V_0 \cdot e^{\frac{-t}{\tau}} \quad \text{(eq.4)}$$

where $\tau = \frac{L}{R}$.

[0047] Which can also be written as:

$$\ln(V_L) = V_0 - \frac{t}{\tau} \quad \text{(eq.5)}$$

[0048] It shall be further noticed that after time t5, the armature/pintle has reached its rest position and thus stopped moving, whereby:

$$\frac{dL}{dt} = \frac{\partial L}{\partial x} \cdot \frac{dx}{dt} = 0$$

[0049] This means in turn that ln(V) is a straight line having a constant slope τ.

[0050] Turning now to Fig.2, the lower graph represents *In(V)* vs. time. As can be seen, *In(V)* describes a wave shape between time t2 and t5, where the falling front approximately coincides with timing M, which is the maximum stroke of the pintle. At time M, *dx/dt=0* and *In (V)* has the same slope as after time t5.

[0051] Now, it shall be appreciated that in the present embodiment the timing of maximum stroke is determined from the voltage feedback and, as shown in Fig.2, the timing of the maximum stroke is approximated as the intersection of the straight line corresponding to *In(V)* after time t5 (when the pintle has reached its closed position) with the curve *In(V)*. The present inventors have indeed observed that this intersection point, indicated by arrow 4 in Fig.2, is strongly correlated with the point of maximum stroke (at M). Furthermore, an injector opening later will show the same pattern as in Fig.2, however shifted to the right, and the same applies to the intersection point.

[0052] In practice, this may be carried out by sampling coil voltage values over an observation window extending from before the max stroke point M to t5, the closing time. The start of the observation window may be determined from calibration and in view of the requested actuating motions. However, in practice, the observation window-indicated 20 in Fig.2-may typically start when the current has become null (at t4).

[0053] Any appropriate program can be used to determine this intersection. The ECU may for example be configured to perform mathematical regression in order to determine an equation fitting the acquired voltage points after t5 as well as an equation fitting the acquired voltage points in the observation window.

[0054] At the end of this step, the timing t_{max} is thus known.

3. Determining the opening time

[0055] Since the pintle is in the ballistic domain, it describes a general bell-shaped trajectory (pintle stroke vs. time - as shown in Fig.1). It shall be appreciated that in the present method it is thus considered that about the same time is required for the pintle to move from the Maximum stroke to its closed position, than from the opening time to the maximum stroke - these motions occurring during the actuating duration.

[0056] Hence, in the present method an actuating duration is calculated as:

$$t_{act} = C \bullet (t_{off} - t_{max}),$$

where C is a coefficient between 1.8 and 2.2, preferably between 1.9 and 2.1. This coefficient C allows some flexibility with respect to the theoretical value 2, since the determination of $t_{max}$is already an approximation of the timing of maximum stroke. While C=2 can be used, coefficient C may also be determined based on calibration. Coefficient C may in particular allow compensating for different pintle speeds at opening and closing.

[0057] The switch-on time is then calculated as:

$$t_{on} = t_{off} - t_{act}$$

4. Use of the opening and closing times

[0058] As is well known in the art, in conventional engine management strategies a fuel command pulse width is determined for each injection event in an engine cycle. Pulse widths are mapped in function of fuel amounts, the latter depending on the requested torque and being corrected using known tools such as e.g. the so-called block learning memory (BLM) and Individual Cylinder Fuel

Control (see e.g. US 6,382,198).

[0059] Hence, for any fuel injection to be performed a pulse width is determined (as well as a corresponding control signal) to command a corresponding opening duration in order to deliver a predetermined fuel amount.

[0060] Injector closing time and opening time information can thus be advantageously employed to improve the injection of fuel quantities, namely of low fuel quantities. A learned correction value may then be determined that is then applied to the pulse width determined by conventional methods.

[0061] In practice, the engine management system may comprise a table of learned closing times that is used for injection control, the table of learned closing times giving normalized, average closing time values for each injector (or cylinder) and a set of pulse widths corresponding to minute fuel injections. Having regard to current injector technologies, it is considered that determining and storing one opening time per injector is sufficient. But it may also be stored in function of fueling quantities, resp. pulse widths.

[0062] The engine may then be controlled with a calibrated map of closing times and opening times, and a pulse width correction may be performed based on a difference between the calibrated and learned closing times as well as calibrated and learned opening times.

Claims

1. A method of controlling an electromagnetic actuator having an excitation coil and a movable armature, wherein an actuating event is triggered by applying a control signal to move said armature from a rest position thereof towards an actuating position, the method comprising the steps of:

    determining a switch-off time (t_{off}) at which the armature returns to its rest position;
    determining a time (t_{max}) at which the armature reaches an extremum of its stroke during said actuation event;
    computing a switch-on time on the assumption that the switch-on time (t_{on}) is separated from the switch-off time by an actuating duration (t_{act}), which represents approximately twice the time separating the extremum stroke time (t_{max}) from the switch-off time (t_{off}).

2. The method according to claim 1, wherein said actuating duration is computed as $t_{act} = C \bullet (t_{off} - t_{max})$, where C is a coefficient between 1.9 and 2.1.

3. The method according to any one of the preceding claims, wherein the said timing t_{max} is determined as the timing at which a curve representative of logarithm of the voltage at the excitation coil during a predetermined observation window before the switch-off time intersects a straight line representative of the logarithm of the excitation coil voltage after the switch-off time.

4. The method according to any one of the preceding claims, wherein said observation window starts after the fall of said control signal for the respective actuating event.

5. The method according to any one of the preceding claims, wherein the determination of the switch-off time (t_{off}) is based on the monitoring of the voltage of said excitation coil of said electromagnetic actuator.

6. The method according to the preceding claim, wherein the determination of the switch-off time (t_{off}) is approximated as the timing when the derivative of the voltage of said excitation coil reaches a local maximum.

7. The method according to any one of the preceding claims, wherein said control signal for a next actuation event is corrected on the basis of said switch-on time.

8. The method according to any one of the preceding claims, wherein said electromagnetic actuator is configured so that its armature drives a pintle in a fuel injector.

9. A method of controlling fuel injection in an internal combustion engine having at least one cylinder with an associated electromagnetically actuated fuel injector for performing injection events, wherein for each injection event a pulse width is determined and a corresponding control signal is applied to the injector's electromagnetic actuator, with which the injector is kept open to spray a desired quantity of fuel, wherein a switch-off time and a switch-on time are determined in accordance with the method according to any one of the preceding claims and subsequently used for injection control.

10. The method according to claim 9, wherein learned correction value(s) is/are elaborated based on said switch-off time and a switch-on time; and said learned correction value(s) is/are used for correcting said pulse width.

11. An internal combustion engine comprising at least one cylinder with at least one fuel injector, wherein said fuel injector comprises a pintle actuated by an electromagnetic actuator having an excitation coil and a movable armature, and wherein said engine comprises an engine management system adapted to trigger an actuating event of said fuel injector by applying a control signal to said electromagnetic ac-

tuator to move said armature, respectively said pintle, from a rest position thereof towards an actuating position and cause a corresponding fuel injection, **characterized in that** said engine management system is configured to:

determine a time (t_{max}) at which the armature reaches an extremum of its stroke during said actuation event;
compute a switch-on time on the assumption that the switch-on time (t_{on}) is separated from the switch-off time by an actuating duration (t_{act}), which represents approximately twice the time separating the extremum stroke time (t_{max}) from a previously determined switch-off time (t_{off}) at which the armature returns to its rest position.

12. The internal combustion engine according to claim 9, wherein said fuel injector has its pintle decoupled from the armature.

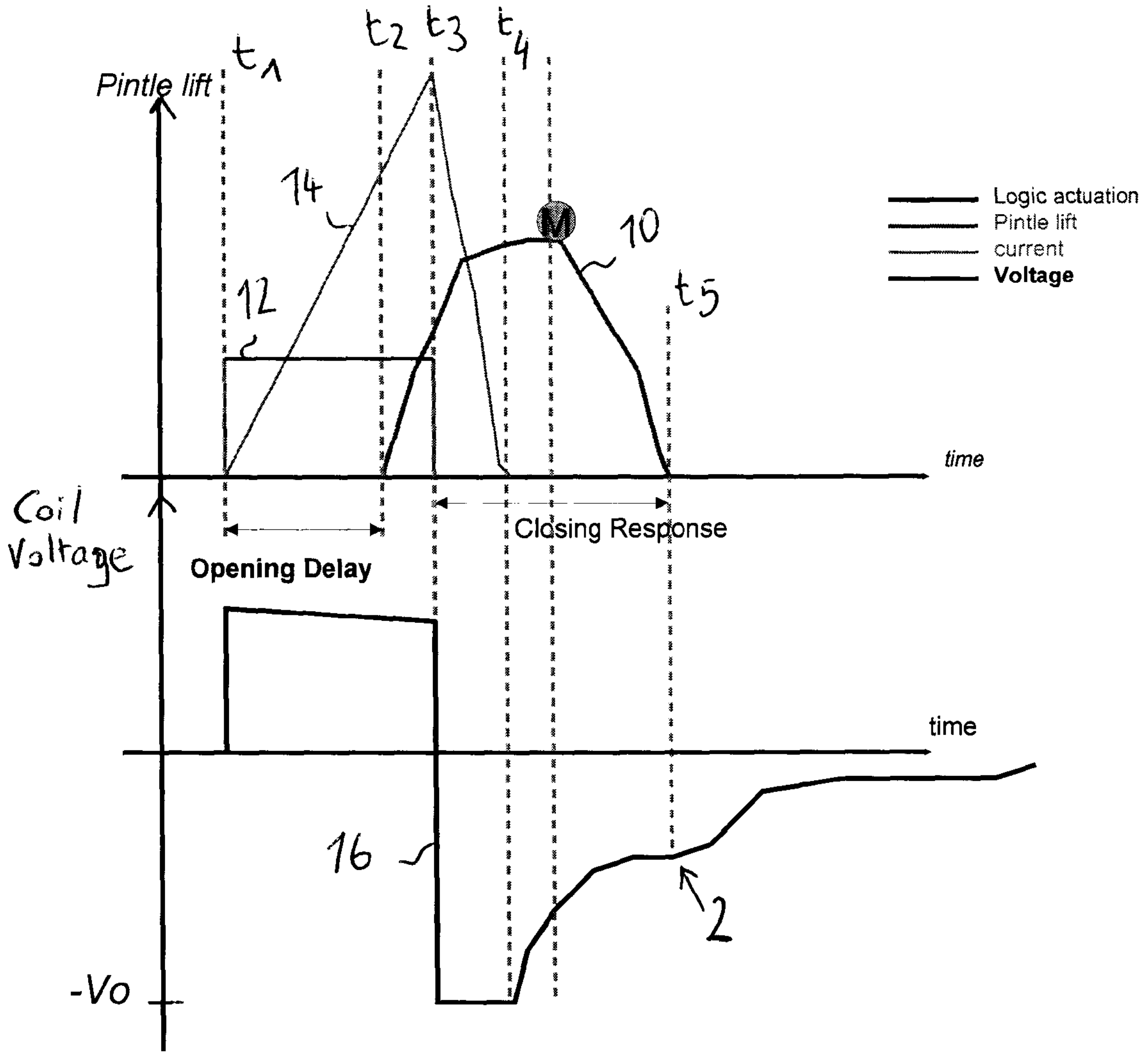
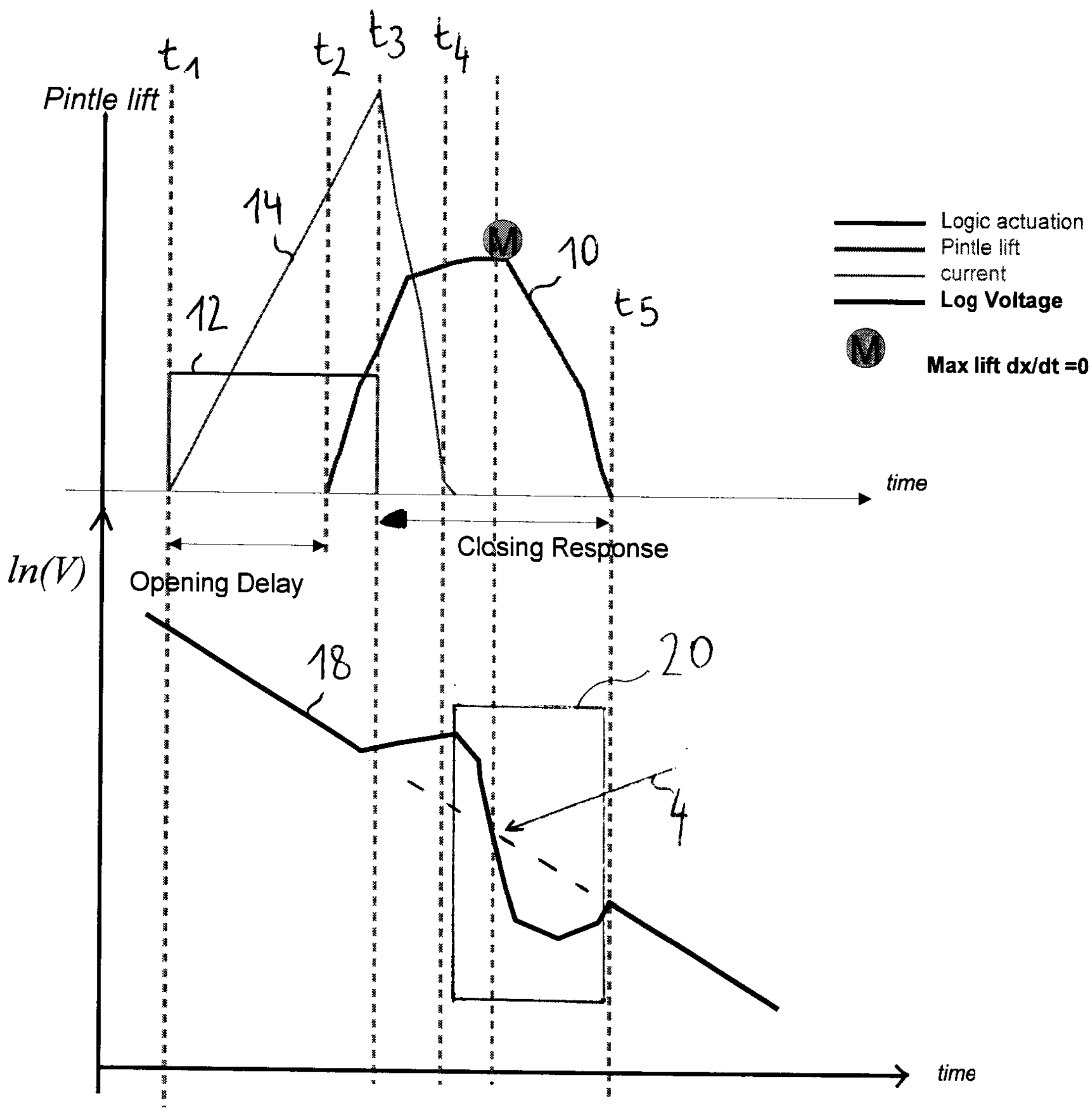

Pintle lift
t1
t2
t3
t4
t5
14
12
10
M
Logic actuation
Pintle lift
current
Voltage
time
Coil Voltage
Opening Delay
Closing Response
time
16
2
-Vo

FIG. 1



t1
t2
t3
t4
t5
Pintle lift
14
12
10
Logic actuation
Pintle lift
current
Log Voltage
Max lift dx/dt =0
time
Opening Delay
Closing Response
ln(V)
18
20
4
time

FIG. 2

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EUROPEAN SEARCH REPORT

Application Number
EP 11 16 3590

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	WO 2011/039043 A1 (BOSCH GMBH ROBERT [DE]; GRIMMINGER CHRISTIAN [DE]; FUCHS EGBERT [DE];) 7 April 2011 (2011-04-07) * abstract; claims 1,2,4-8; figure 4a * * page 11, line 1 - page 12, line 4 * -----	1,2,7-12	INV. F02D41/20
X	DE 10 2008 040222 A1 (BOSCH GMBH ROBERT [DE]) 14 January 2010 (2010-01-14) * abstract; claims 1,2,7,8; figures 2,3 * * paragraph [0030] - paragraph [0045] * -----	1,7-12	
A	DE 40 11 217 A1 (LUCAS IND PLC [GB]) 10 October 1991 (1991-10-10) * abstract; claim 1; figures 2a-2e * * column 4, line 12 - column 5, line 7 * -----	3-6	
A	DE 10 2009 027290 A1 (BOSCH GMBH ROBERT [DE]) 15 April 2010 (2010-04-15) * abstract; claims 1-4; figures 2a,2b,4 * * paragraph [0042] - paragraph [0055] * -----	1	TECHNICAL FIELDS SEARCHED (IPC) F02D

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	23 September 2011	Van der Staay, Frank

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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D : document cited in the application
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2

EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 11 16 3590

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23-09-2011

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

REFERENCES CITED IN THE DESCRIPTION

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- US 6382198 B **[0058]**