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(54) METHOD FOR DETECTING A FAILED ACTUATION OF A SWITCHABLE SOLENOID VALVE, ELECTRONIC CIRCUIT FOR PERFORMING THE METHOD, PUMP AND MOTOR VEHICLE

(57) The invention is concerned with a method for detecting a failed actuation of a switchable solenoid valve (15), wherein in at least one actuation cycle (34) an electric current (I) is driven through the solenoid (18) of the valve (15) for closing the valve (15) with a predefined actuation energy (E) and for holding the valve (15) closed in a subsequent hold phase (37), wherein in the hold phase (37) a current strength value of the electric current (I) is controlled by switching a voltage source (U). The invention is characterized in that a switching frequency (F) at which the controller (17') switches the voltage source (U) is measured and if the switching frequency (F) fulfills a predefined failure criterion (46) in one actuation cycle (34), a signal signals that the current actuation cycle (34) is a failure cycle (43) in which the valve (15) did not close.

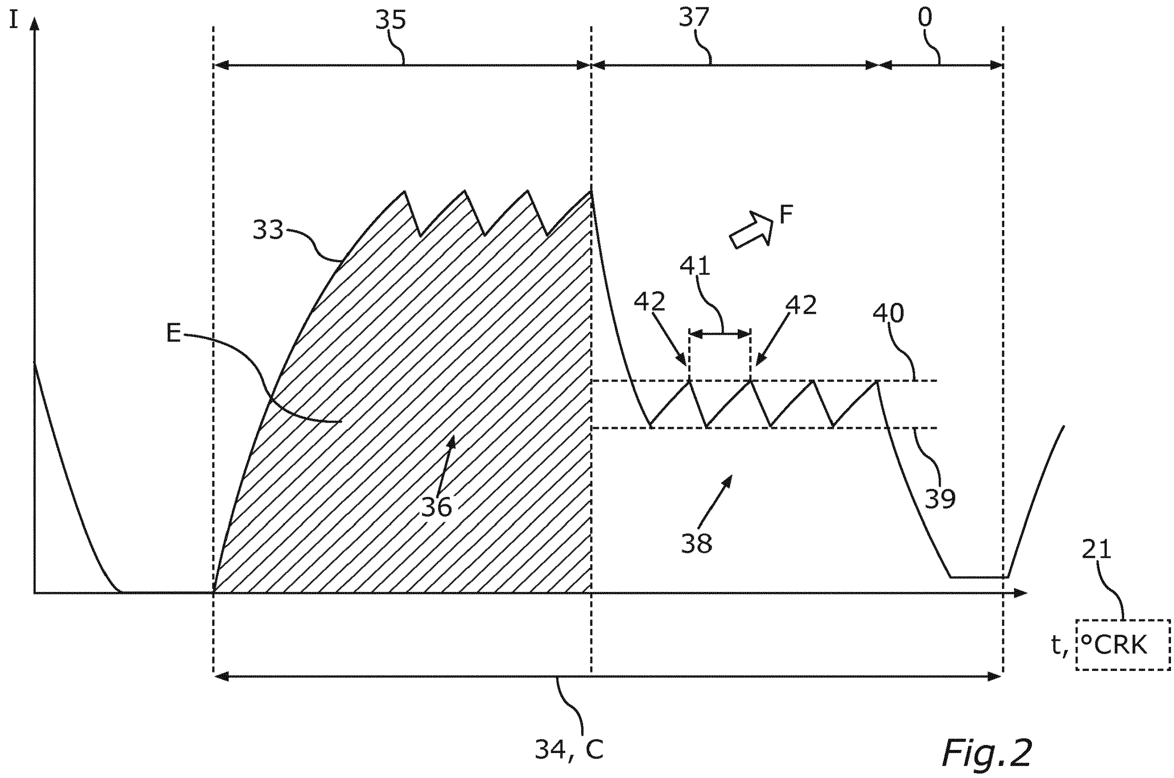

Fig.2

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Description

[0001] The invention is concerned with a method for detecting a failed actuation of a switchable solenoid valve. The invention is also directed to an electronic circuit for controlling a switchable solenoid valve. The invention also comprises a pump for an injection system of a motor vehicle and a motor vehicle comprising the injection system.

[0002] One of the most used actuators for controlling the flow of a fluid is the solenoid valve. There are two main types of solenoid valves, the proportional valve and the digital valve. As an example, in diesel and gasoline common rail fuel injection systems, the rail pressure can be controlled by a digital inlet valve (DIV).

[0003] The DIV is a solenoid valve which closes the inlet valve when it is energized, i.e. when an electric current is driven through the solenoid of the valve for closing the valve against a force of a spring. During a currentless state, the valve will open and be kept in open position by the DIV spring until the solenoid is energized again. The current profile for the DIV is a peak current and a hold current control. The peak current provides an actuation energy for moving the valve from an open position into the closed position. The hold current generates the magnetic field for keeping the valve in the closed position.

[0004] Due to the fast switching of a digital inlet valve especially in a pump for a fuel injection system, unwanted noise emission and component wear occur when the valve hits the respective end position during closing (DIV actuation by energizing the solenoid) and during opening (by spring force).

[0005] It is possible to reduce this noise emission by optimizing the DIV control pulse, i.e. the peak current for providing the actuation energy. The basic concept of reducing the noise emission is to reduce the end velocity of the valve before hitting one or both end positions. This can be achieved by providing only the necessary actuation energy during valve closing and by providing only a small energy to decelerate the valve during valve opening.

[0006] However, the actuation energy for the actuation should not be reduced to a lesser level or stage, i.e. where the valve does not close anymore. Otherwise, in the case of a pump for an injection system, a failed pump delivery stroke will occur and a fuel pressure control issue will be created.

[0007] Therefore, in order to find the minimum energy to actuate the valve, it is necessary to develop a feedback concept on how to detect a failed actuation of the valve. Thus it can be ensured that the core function of the switchable solenoid valve, i.e. the actuation or closing, can be provided while at the same time noise emission and component wear are reduced.

[0008] US 2012/0167993 A1 describes a method for reducing the noise generated when closing the inlet valve of a fuel pressure system. The duration of the peak current for providing the actuation energy is varied. However, this method implies that it is known, how far the acceleration or in general the actuation energy may be reduced without causing a failure of the actuation.

[0009] US 8 245 693 B2 describes a method for reducing the noise in the closing state of an inlet valve of a high pressure injection system by reducing the amplitude of the peak current and at the same time letting the peak current flow for a longer time such that the velocity of the accelerated valve is reduced. This slows the pump down.

[0010] It is an object of the present invention to detect a failed actuation of a switchable solenoid valve. The detection is especially needed for adapting the actuation energy that is applied for closing the valve, wherein the actuation energy shall be reduced to such a degree that the energy is minimized, while the actuation of the solenoid valve is still successful.

[0011] The object is solved by the subject matter of the independent claims. Further aspects of the invention are described in the dependent claims, the following description and the figures.

[0012] The invention provides a method for detecting a failed actuation of a switchable solenoid valve. In at least one actuation cycle (comprising one closing phase and one opening phase of the valve) an electric current is driven through the solenoid of the valve for closing the valve against a force of a spring. The electric current generates a magnetic field for magnetically attracting a moveable part of the valve, e.g. a valve disc and a pin. The electric current provides a predefined actuation energy for closing the valve. The energy depends on the effective electric voltage and the duration. For holding the valve open, the electric current is driven through the solenoid in a subsequent hold phase that follows the closing of the valve. Then, the electric current may be interrupted for letting the spring open the valve again.

[0013] In the hold phase a current strength value of the electric current is controlled by a controller by switching on a current source, if the value is smaller than a lower threshold value, and switching off the current source, if the value is greater than an upper threshold value. This type of control is called two value control or bang-bang control and is described, e.g., in the above cited documents. Switching off the voltage source means that the solenoid is disconnected from the voltage source such that an increase of the current is prevented. However, the current may continue flowing due to the induction of the electric circuit, especially the solenoid. To this end, a freewheeling diode may be provided.

[0014] For reducing the noise emitted by the valve during the closing of the valve, the actuation energy may be varied like it is described in the above documents. However, if the actuation energy is too low, the actuation fails. For detecting a failed actuation, a switching frequency at which the controller switches the current source in the hold phase is measured and if the switching frequency fulfills a predefined failure criterion in one actuation cycle, a signal is generated, wherein the signal signals that the current actuation cycle is a failure cycle in which the valve did not close. In other words, a change of current control frequency of the controller in the hold phase is detected. The current strength or the dynamic change of the current strength or level during hold phase (during the hold phase the valve should be completely actuated, i.e. closed) is controlled via the described two value control method or bang-bang closed loop current control. It includes an upper control threshold and a hysteresis resulting in the lower threshold value. By observing the current frequency during the hold phase, a significant relative change in control frequency can be detect between a successful actuation and a failed actuation. The frequency of the control is mainly influenced by the current gradient which in turn depends on the circuit induction of the magnetic circuit of the solenoid valve. When the actuation is successful (valve is closed), the pole distance between the pole-piece and armature is smaller, i.e. the pin of the valve is moved closer to the solenoid as compared to the open state. Therefore, the circuit induction is higher and current gradient is lower. As a result, the control frequency or switching frequency in the hold phase is lower, when the valve is successfully actuated as compared to a failed actuation (valve still open) . This means, once the energy level of the actuation energy is reduced below a minimum required energy value for actuating the solenoid valve, a relative change in control frequency or switching frequency in the hold phase can be detected. This can be used as a feedback to detect failed actuation. The necessary degree of relative change can be defined by the said failure criterion. The failure criterion can be derived in simple experiments.

[0015] The invention also comprises further aspects that provide additional technical advantages.

[0016] The described method is a core element that can be used for several different applications. One application is the minimization of the amount of actuation energy that is used for the process of closing the valve, i.e. moving the valve from the open position into the closed position. This is achieved by the described peak current. For minimizing the amount of actuation energy and therefore minimizing the noise generated during the actuation, several consecutive actuation cycles are performed, i.e. the valve is closed and open several times. For each consecutive actuation cycle the actuation energy provided for closing the valve is reduced and, if a failure cycle is detected (i.e. the valve does not actually close), a parameter value characterizing the amount of actuation energy of the actuation cycle that immediately preceded the failure cycle, is signaled to be the parameter value for a minimum possible actuation energy. This parameter value indicates the minimum possible actuation energy for successfully closing the valve. For example, the parameter value can characterize a duration and/or maximum value of an impulse of the current that is applied for providing the actuation energy. For changing or varying the actuation energy, the parameter value is changed stepwise, once for each consecutive actuation cycle. In other words, the duration or time for applying the pulse current that is supposed to accelerate the valve and to move it into the closed position, is shortened with each actuation cycle. If the valve does not close anymore in one actuation cycle, the parameter value preceding that failure cycle is the smallest amount of actuation energy, i.e. the shortest impulse possible.

[0017] The parameter value can be saved in an electronic circuit of the valve for controlling future actuation cycles. In other words, the electronic circuit can be calibrated to use or apply the minimum possible actuation energy. Thus the calibration guarantees the operation of the valve with minimum noise and minimum component wear.

[0018] For example, the parameter value can be determined during an end-of-line calibration procedure after producing the valve.

[0019] This provides a low-cost strategy for individually calibrating a specific valve with regard to noise and/or component wear. Due to production tolerances, each valve may have a different optimal parameter value and for each specific valve the parameter value can be determined after the production. As a valve also changes in its mechanical and/or magnetic and/or electric behavior during its lifetime, the parameter value may also be determined during a self-calibration procedure after the valve has been used for at least a predetermined amount of time, i.e. after more than one week and/or year. Thus, the parameter value may even be adapted during operation of the valve.

[0020] The failure criterion that is used to detect a failure cycle may comprise that the switching frequency that results during the hold phase is above a predefined frequency threshold. In other words, an absolute value can be provided and the switching frequency is compared to this absolute value. Additionally or alternatively a relative or absolute change of the switching frequency compared to a switching frequency of a preceding actuation cycle may be detected and the failure criterion may comprise that this relative or absolute change is greater than a predefined change threshold value. In other words, a step or jump of the switching frequency is detected with regard to a preceding actuation cycle. Determining the relative change provides the advantage that the method does not have to be adapted to a value of the switching frequency that is applied by the controller in the case that the valve is closed successfully.

[0021] For measuring the switching frequency, one aspect of the invention comprises sensing a current strength signal of the electric current and determining a time difference between at least two predefined characteristic points of the signal. For example, a time difference between peaks of the signal can be measured or determined. This can be repeated for each measurement.

[0022] As was already explained, the method is especially useful for calibrating a high-pressure pump of a fuel injection system of a motor vehicle. Correspondingly, as the valve an inlet valve of the high-pressure pump of the injection system of the motor vehicle is controlled. "High-pressure" especially means that the pump generates a pressure greater than 100 bar.

[0023] For performing the inventive method, the invention also provides an electronic circuit for controlling a switchable solenoid valve. The electronic circuit is designed to perform an embodiment of the inventive method as described. The electronic circuit may comprise a microcontroller or a microprocessor for performing the steps of the method. The electronic circuit may provide said controller.

[0024] The invention also comprises a pump for a fuel injection system of a motor vehicle, wherein the pump comprises the described switchable solenoid valve, particularly a digital inlet valve, and an embodiment of the inventive electronic circuit.

[0025] Finally, the invention is concerned with a motor vehicle comprising an internal combustion engine with an injection system. The vehicle provides an injection system that comprises an embodiment of the inventive pump with the described electronic circuit.

[0026] In the following an exemplary implementation of the invention is described. The figures show:

Fig. 1 a schematic illustration of an embodiment of the inventive motor vehicle;

Fig. 2 a diagram illustrating a current strength signal of an electric current of a solenoid of a pump of the motor vehicle of Fig. 1; and

Fig. 3 a diagram illustrating a switching frequency of a controller of the valve.

[0027] The embodiment explained in the following is a preferred embodiment of the invention. However, in the embodiment, the described components of the embodiment each represent individual features of the invention which are to be considered independently of each other and which each develop the invention also independently of each other and thereby are also to be regarded as a component of the invention in individual manner or in another than the shown combination. Furthermore, the described embodiment can also be supplemented by further features of the invention already described.

[0028] In the figures elements that provide the same function are marked with identical reference signs.

[0029] Fig. 1 shows a motor vehicle 10 that can be, e.g., a passenger vehicle or a freight vehicle. The motor vehicle 10 may comprise an internal combustion engine 11 that may be operated on the basis of fuel 12 from a fuel tank 13. The fuel 12 may be pumped from the fuel tank 13 to the combustion engine 11 by a pump 14. The pump 14 may comprise a switchable solenoid valve 15, e.g. a digital inlet valve, DIV, with a valve disc 16 and an electric coil or solenoid 18. An electric current I for the solenoid 18 may be controlled by an electronic circuit 17 that provides a control unit or controller 17' for switching the current I. The operation of the valve 15 can be coordinated with the rotation of a crank 20 by measuring a crank angle 21 and switching current I according to crank angle 21. Crank angle 21 may be measured using a sensor 21'. Crank 20 moves a piston 21 for a pumping movement 23 for pumping the fuel 12 from a low pressure side 24 to a high-pressure side 25 where the fuel 12 is injected by a fuel injection system. Outlet valve 26 may be a passive valve, e.g. a check valve, wherein the inlet valve is provided by the solenoid valve 15 with its valve disc 16. For closing the valve 15, current I is driven through solenoid 18 such that a pin 27 that holds the valve disc 16 is attracted against a spring force of a spring 28 towards a pole piece 29 and an armature such that valve disc 16 is moved from an open position 31 to a closed position 32. Current I may be provided by a voltage source U.

[0030] Switching off voltage source U results in an exponential decrease of current I. Once the spring force of the spring 28 is stronger than the magnetic field of solenoid 18, the valve disk 16 is moved back from closed position 32 to open position 31. This completes a full actuation cycle or pump cycle.

[0031] Fig. 2 shows a current strength signal 33 of current I over time t or over crank angle 21 (°CRK). During a pump cycle or actuation cycle 34 (C)during an actuation phase 35 a peak current 36 is provided that delivers an overall actuation energy for moving valve disc 16 from the open position 31 to the closed position 32. Actuation energy E is symbolically represented by the area under signal 33 in the actuation phase 35. Once valve disc 16 is in closed position 32, a hold phase 37 follows with a hold current 38. Controller 17' controls current I during hold phase 37 using a bang-bang control method by switching on the voltage source U, if the value of current I is smaller than a lower threshold value 39, and switching off voltage source U, if the value of current I is greater than an upper threshold value 40. After holding phase 37 an opening phase O may follow in which current I is allowed to fall to zero such that spring 28 may open valve 16 again.

[0032] Electronic circuit 17 may measure a time difference 41 between e.g. two consecutive peaks 42 of the signal 33. The inverse value of time difference 41 yields a switching frequency F, i.e. the frequency or rate at which controller 17' switches current I. The switching frequency F is dependent on the induction value of the magnetic system of solenoid 18 and the magnetic materials and their position within pump 15. In other words, the position of valve 16 and pin 27 influences switching frequency F.

[0033] Fig. 3 shows, how this can be used to minimize the amount of actuation energy during actuation phase 35. During several consecutive actuation cycles 34 (cycle N, N+1, N+2, N+3), the actuation energy E may be reduced stepwise, such that for each actuation cycle less actuation energy E is provided during actuation phase 35. Fig. 3 shows that actuation cycle N+2 is a failure cycle 43 in which the solenoid valve 15 does not close due to insufficient actuation energy E. Consequently, a change of the value of the induction of the magnetic circle results and a relative change 44 of the switching frequency F from the preceding actuation cycle 45 to failure cycle 43 is greater than a predefined threshold value 46. Threshold value 46 is a failure criterion that is fulfilled in actuation cycle N+2.

[0034] Thus the parameter value used for changing the actuation energy E, for example the duration of actuation phase 35, can be set to the value used for the preceding cycle 45 in order to obtain an operation of solenoid valve 15 with minimum actuation energy E.

[0035] This is a low-cost strategy to detect failed actuation of a solenoid valve, especially a digital solenoid valve.

[0036] Overall, the example shows how a method for detecting a failed actuation of a switchable solenoid valve is provided by the invention.

Claims

1. Method for detecting a failed actuation of a switchable solenoid valve (15), wherein in at least one actuation cycle (34) an electric current (I) is driven through the solenoid (18) of the valve (15) for closing the valve (15) against a force of a spring (28) with a predefined actuation energy (E) and for holding the valve (15) closed in a subsequent hold phase (37), wherein in the hold phase (37) a current strength value of the electric current (I) is controlled by a controller (17') by switching on a voltage source (U), if the value is smaller than a lower threshold value (39), and switching off the voltage source (U), if the value is greater than an upper threshold value (40), **characterized in that** a switching frequency (F) at which the controller (17') switches the voltage source (U) is measured and if the switching frequency (F) fulfills a predefined failure criterion (46) in one actuation cycle (34), a signal is generated, wherein the signal signals that the current actuation cycle (34) is a failure cycle (43) in which the valve (15) did not close.

2. Method according to claim 1, wherein several consecutive actuation cycles (34) are performed and for each consecutive actuation cycle (34), the actuation energy (E) provided for closing the valve (15) is reduced and, if a failure cycle (43) is detected, a parameter value characterizing the amount of actuation energy (E) of the actuation cycle (45) that preceded the failure cycle (43), is signaled to be the parameter value for a minimum possible actuation energy (E).

3. Method according to claim 2, wherein the parameter value characterizes a duration and/or maximum value of an impulse (36) of the current that is applied for providing the actuation energy (E).

4. Method according to claims 2 or 3, wherein the parameter value is saved in an electronic circuit (17) of the valve (15) for controlling future actuation cycles (34).

5. Method according to one of claims 2 to 4, wherein the parameter value is determined during an end-of-line calibration procedure after producing the valve (15) and/or during a self-calibration procedure after the valve has been used for at least a predefined amount of time.

6. Method according to any of the preceding claims, wherein the failure criterion (46) comprises that the switching frequency (F) is above a predefined frequency threshold value and/or that a relative or absolute change (44) of the switching frequency (F) compared to a switching frequency (F) of a preceding actuation cycle (45) is greater than a predefined change threshold value (46).

7. Method according to any of the preceding claims, wherein the switching frequency (F) is measured by sensing a current strength signal (33) of the electric current (I) and determining a time difference (41) between at least two predefined characteristic points (42) of the signal (33).

8. Method according to any of the preceding claims, wherein as the valve (15) an inlet valve of a high pressure pump (14) of an injection system of a motor vehicle (10) is controlled.

9. Electronic circuit (17) for controlling a switchable solenoid valve (15), wherein the electronic circuit (17) is designed to perform a method according to any of the preceding claims.

10. Pump (14) for an injection system of a motor vehicle (10), wherein the pump (14) comprises a switchable solenoid valve (15), particularly a digital inlet valve, and an electronic circuit (17) according to claim 9.

11. Motor vehicle (10) comprising an internal combustion engine (11) with a fuel injection system that provides a pump (14) according to claim 10.

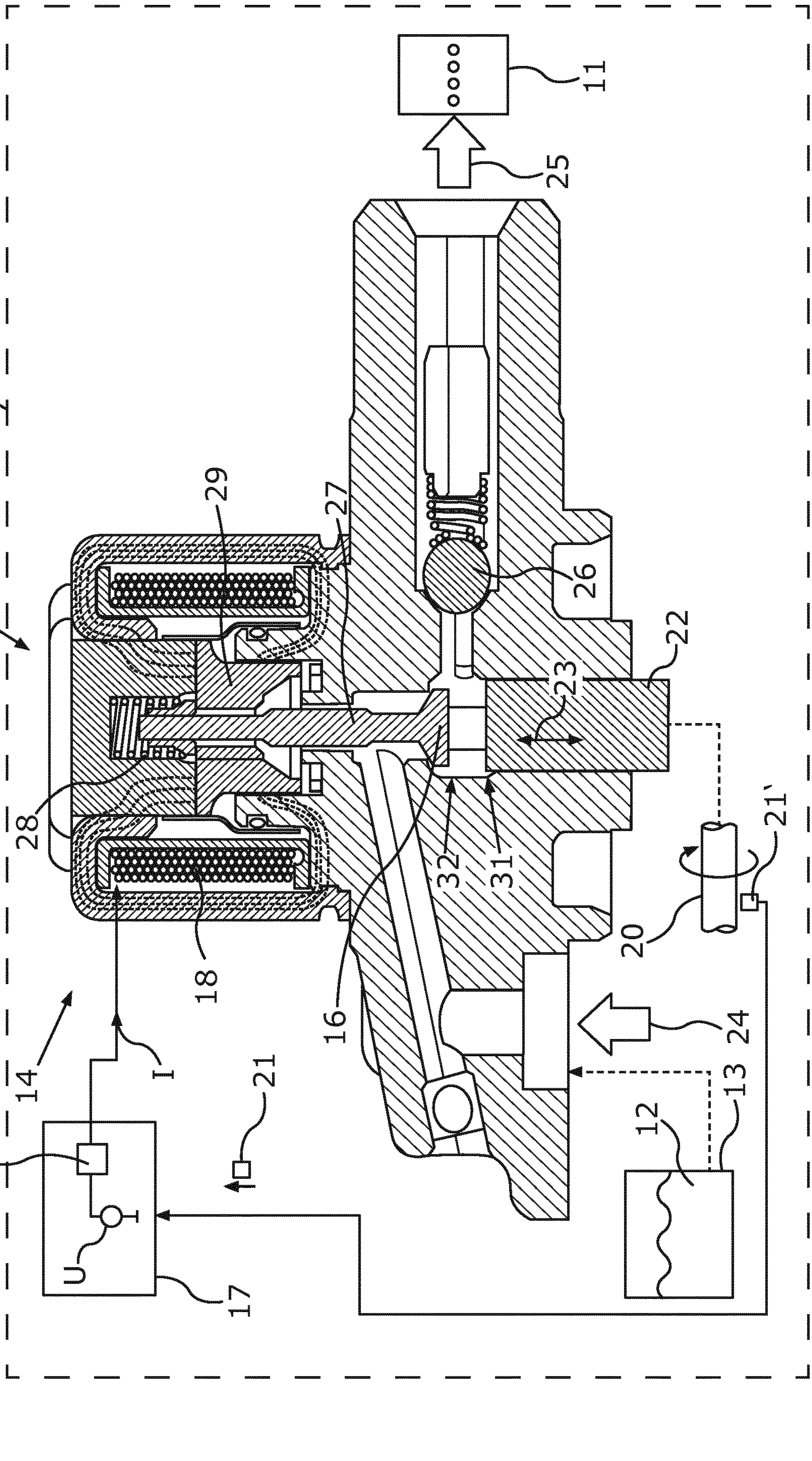

Fig.1

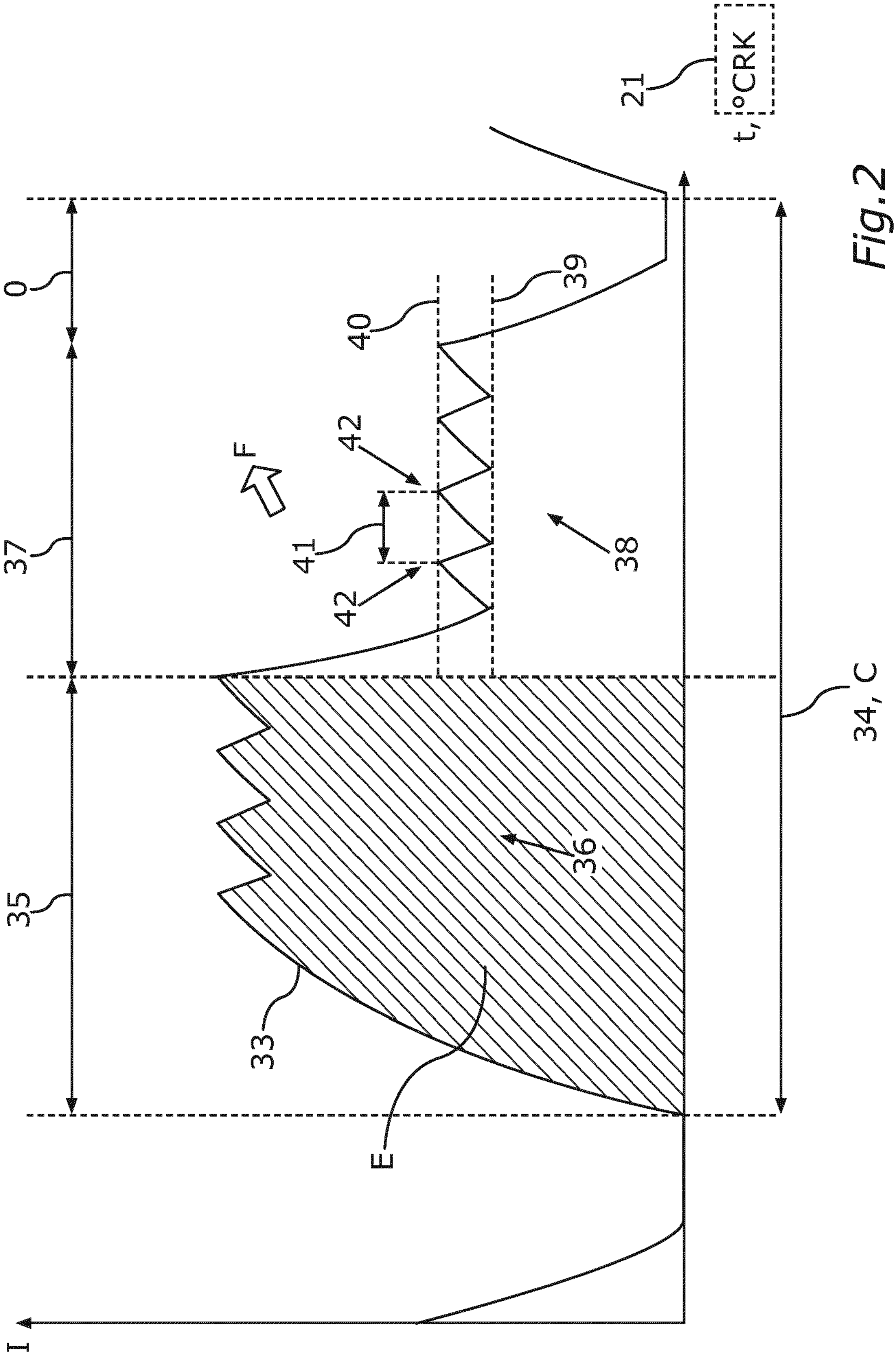

Fig.2

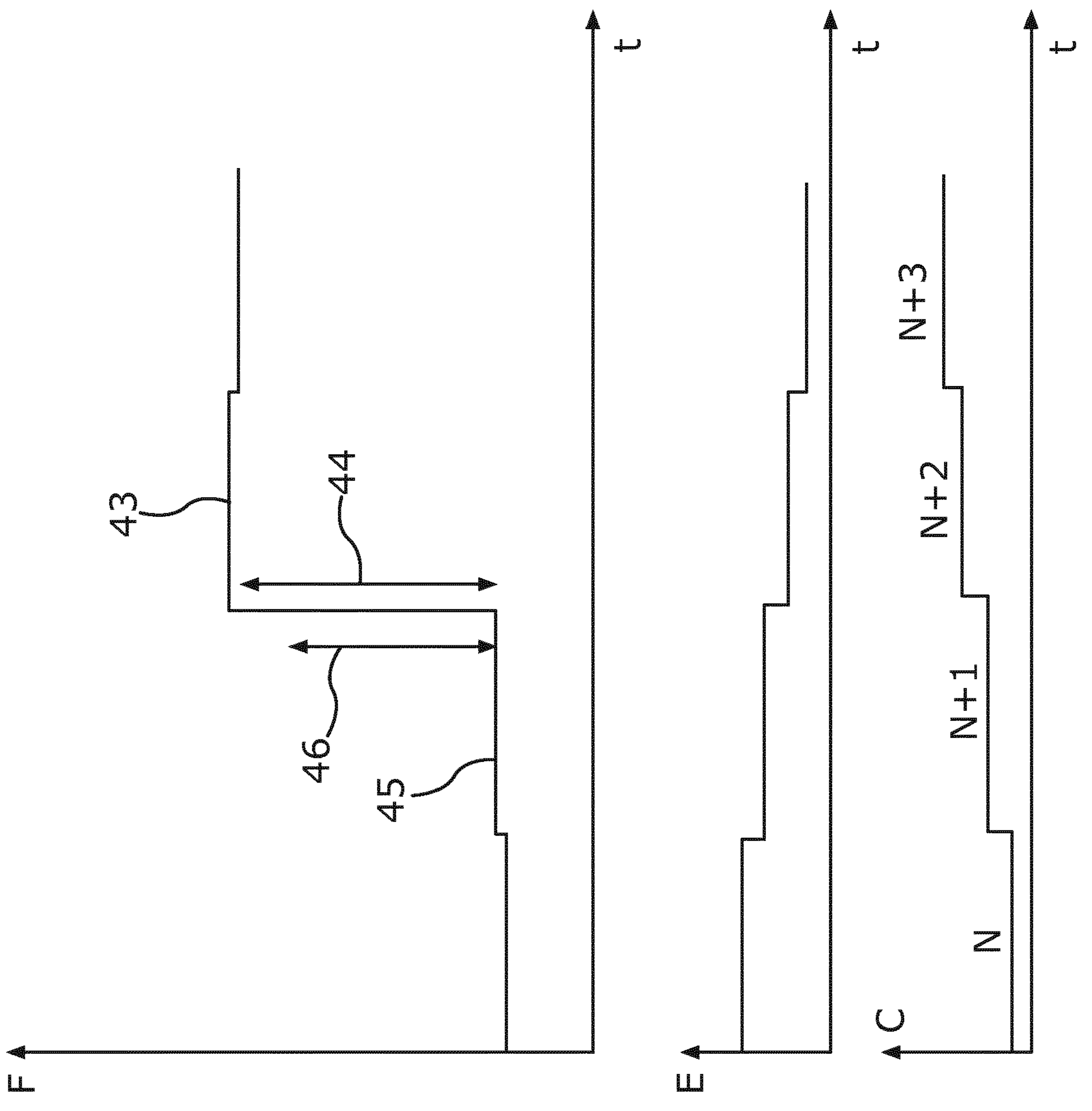

Fig.3

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EUROPEAN SEARCH REPORT

Application Number
EP 17 16 5221

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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	6 September 2017	Le Bihan, Thomas

CATEGORY OF CITED DOCUMENTS

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EUROPEAN SEARCH REPORT

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