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(56) Documents Cited:
WO 2005/081332 A1 **WO 2003/065468 A2**

(58) Field of Search:
INT CL **F02M, H01L**
Other: **WPI, EPODOC, TXTE**

(54) Abstract Title: **Variable-frequency polarization of a piezoelectric actuator**

(57) A piezoelectric actuator (2, fig 1) for a fuel injection valve (1, fig 1) has an actuator body (23, fig 1) that comprises a plurality of ceramic layers (26, 27, fig 1) and a plurality of electrode layers (28, 29, fig 1) disposed between the ceramic layers (26, 27, fig 1). The domain structures in the ceramic layers are formed by variable frequency polarization, which may be effected in three intervals T1, T2, T3. Upon the transition to a subsequent interval of the variable frequency polarization, the frequency f of the polarizing voltage is reduced and the amplitude of the polarizing voltage is increased.

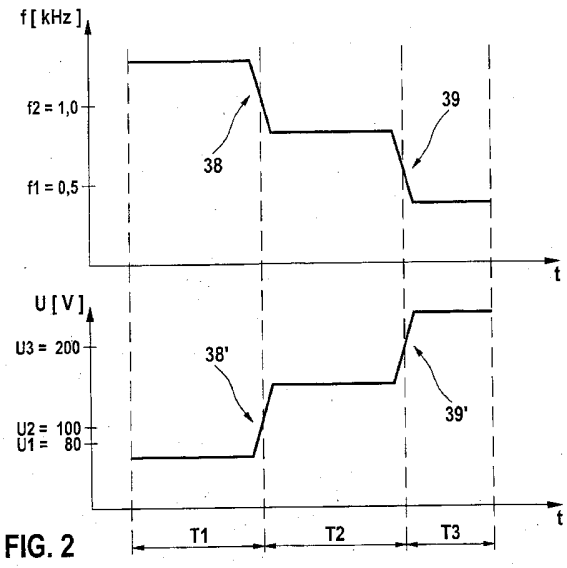

FIG. 2

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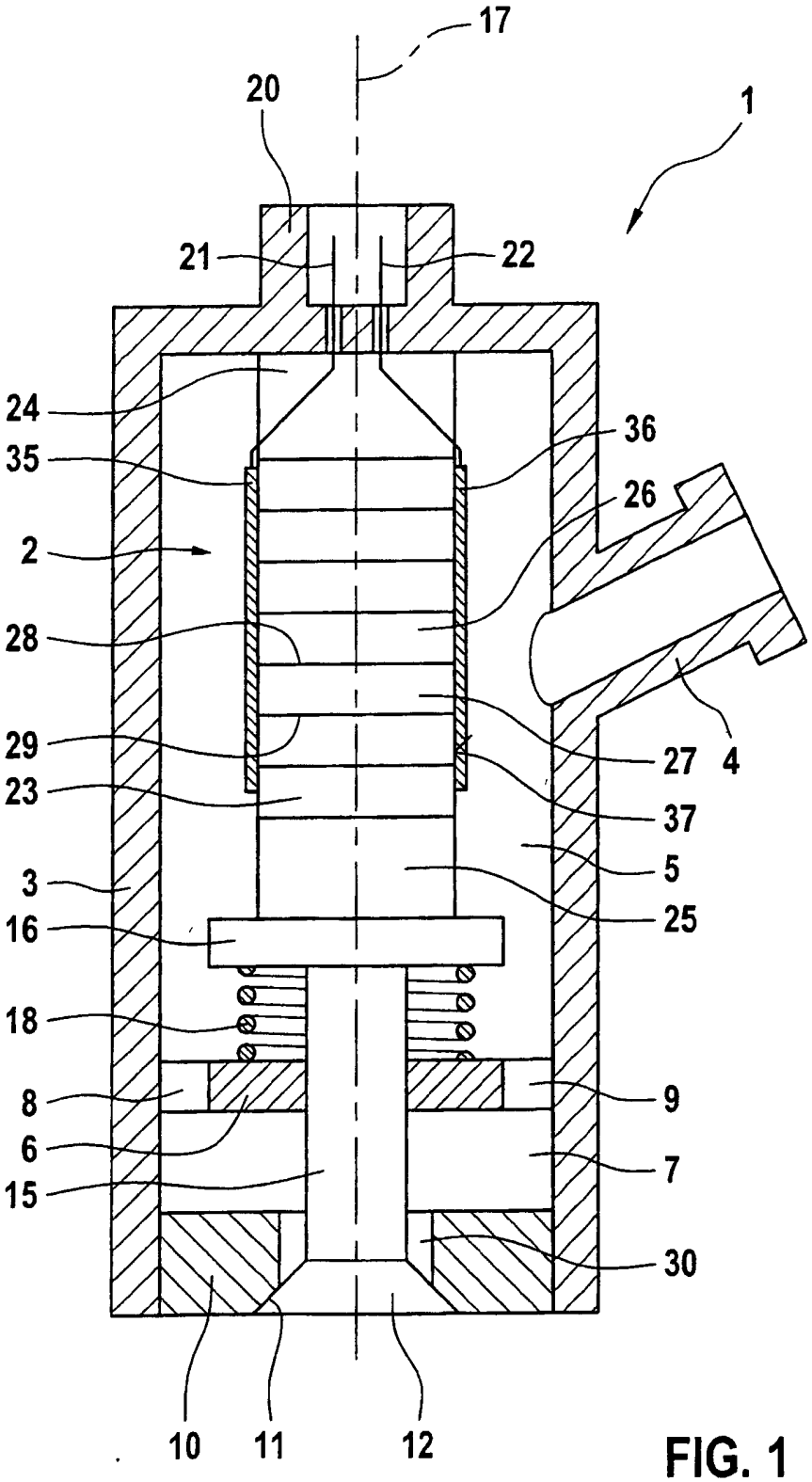
17
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18
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12

FIG. 1

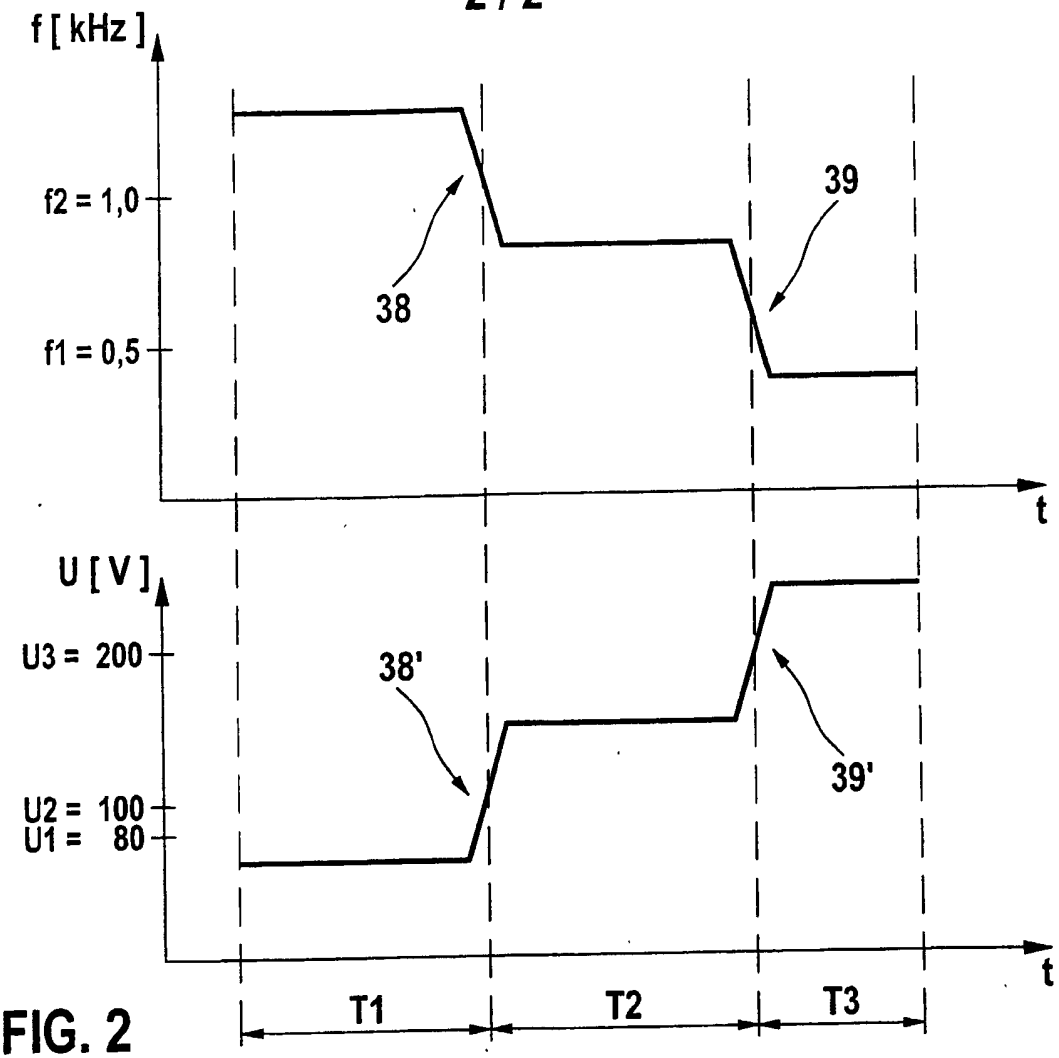
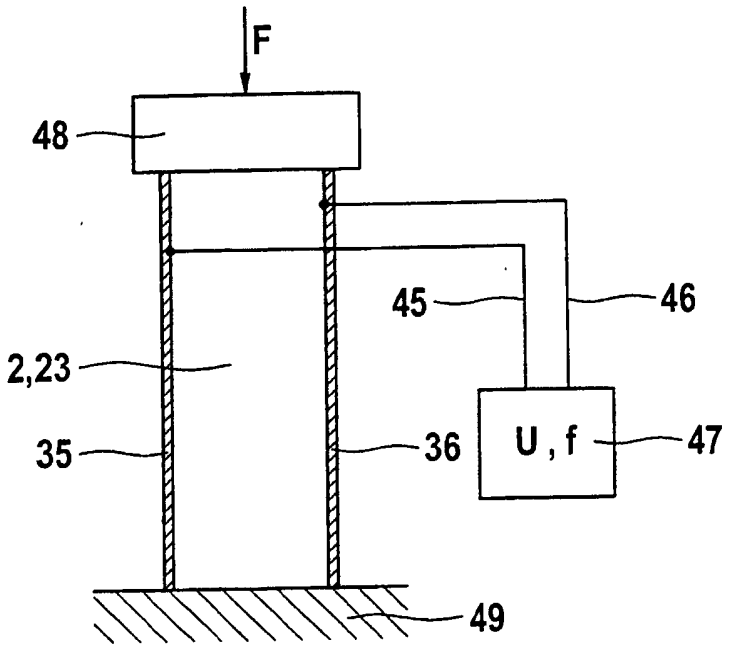

f [kHz]
f2 = 1,0
f1 = 0,5
38
39
t
U [V]
U3 = 200
U2 = 100
U1 = 80
38'
39'
t
T1
T2
T3

FIG. 2


F
48
45
46
2,23
35
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U , f
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FIG. 3

Description

Title

Piezoelectric actuator

Background art

The invention relates to a piezoelectric actuator for a fuel injection valve and to a fuel injection valve having such a piezoelectric actuator. In particular, the invention relates to the field of injectors for fuel injection systems of air-compressing, auto-ignition internal combustion engines.

From DE 100 62 672 A1 a piezoceramic component, comprising a stack of at least two ceramic layers and an electrode layer disposed between the two ceramic layers, and a method of manufacturing it are known. The known piezoceramic components as a rule comprise many layers and are usable for example as actuators in piezostacks in that a low-inertia mechanical deflection of comparatively high force is achieved by means of voltage triggering.

During the manufacture of such a piezoelectric component it is conceivable that the component is heated to a specific temperature and then cooled under the action of a direct voltage in order to achieve a polarization. In this case, it is desirable that, later, during operation of the component a defined deformation is achieved when a specific voltage is applied. During the polarization of the piezoelectric component there is however the danger of polarization cracks arising in the ceramic layers and

impairing the function of the piezoelectric component while in operation.

Disclosure of the invention

The piezoelectric actuator according to the invention having the features of claim 1 and the fuel injection valve according to the invention having the features of claim 13 have the advantage of enabling relatively economical manufacture while in particular guaranteeing a high degree of reliability and operating ability.

Advantageous developments of the piezoelectric actuator indicated in claim 1 and of the fuel injection valve indicated in claim 13 are possible by means of the measures outlined in the sub-claims.

The trigger voltage may be described by an a.c. voltage with a superimposed direct voltage, thereby resulting in a positive a.c. voltage profile. Preferably in this case a trapezoidal profile or the like is selected in order to guarantee a high energy input.

Advantages of variable frequency polarization are ratio aspects and an advantageous formation of polarization cracks. With regard to ratio, it is optionally possible to eliminate the hot poling process step, thereby dispensing with the use of a furnace.

A crucial point during the variable frequency polarization is the utilization of the self-heating of the actuator body during a trigger operation, for example a pulsed trapezoidal trigger operation.

It is advantageous if the variable frequency polarization is effected in a plurality of intervals, wherein upon a transition to a subsequent interval of the variable frequency polarization a frequency of a trigger voltage is reduced and an amplitude of the trigger voltage is increased. This has the advantage of allowing the actuator body to be protected against mechanical and/or thermal overload. One of the effects that may therefore be achieved is that at the start of the frequency polarization substantially a heating of the material of the actuator body occurs and later the desired structures may be formed in the material of the actuator body. In this case, it is advantageous if the variable frequency polarization comprises at least three intervals that occur in chronological succession. It is however also possible to provide further intermediate intervals. In the first interval a relatively high frequency and a relatively low amplitude of the trigger voltage are selected, so that a heating of the ceramic layers occurs. This moreover enables rearrangement- and diffusion processes in a solder. The temperature in this case may be for example 120°C. In the second interval the frequency is slightly reduced and the amplitude of the trigger voltage is increased, thereby resulting in a specific transition interval. In the third interval, which is used for polarization, the frequency is further reduced and the amplitude of the trigger voltage is increased, this possibly resulting in a temperature rise to for example more than 150°C. The duration of the third interval may be for example 30 s or more. To prevent thermal damage to a soldered connection and/or to an enamel coating on the actuator surface temperature regulation has

to be provided, in which case for example fans are installed and used for the temperature regulation.

It is advantageous if a signal shape of the trigger voltage for the variable frequency polarization is trapezoidal. This has the advantage of enabling a relatively high energy input compared to a sinusoidal shape.

It is further advantageous if there is a specific mechanical bias of the actuator body during the frequency polarization, for example by means of a biasing force of 200 N or more. This has the advantage that the formation of polarization cracks may be advantageously influenced.

Brief description of the drawings

Preferred embodiments of the invention are explained in detail in the following description with reference to the accompanying drawings, in which like elements are provided with identical reference characters. The drawings show:

Fig. 1 a schematic sectional representation of a fuel injection valve having a piezoelectric actuator in accordance with an embodiment of the invention;

Fig. 2 a frequency characteristic and an amplitude characteristic of a trigger voltage during a variable frequency polarization operation for the manufacture of the piezoelectric actuator of the fuel injection valve of the embodiment of the invention and

Fig. 3 a simplified representation of the piezoelectric actuator of the fuel injection valve of the embodiment of the invention during its manufacture.

Forms of implementation of the invention

Fig. 1 shows a fuel injection valve 1 having a piezoelectric actuator 2 in accordance with an embodiment of the invention. The fuel injection valve 1 may be used in particular as an injector for fuel injection systems of air-compressing, auto-ignition internal combustion engines. A preferred use of the fuel injection valve 1 is for a fuel injection system having a common rail that carries diesel fuel under high pressure to a plurality of fuel injection valves 1. The piezoelectric actuator 2 according to the invention is suitable in particular for such a fuel injection valve 1 and also for inverse triggering of the piezoelectric actuator 2. The fuel injection valve 1 according to the invention and the piezoelectric actuator 2 according to the invention are however also suitable for other applications.

The fuel injection valve 1 has a valve housing 3 and a fuel intake connecting piece 4 connected to the valve housing 3. A fuel line is attachable to the fuel intake connecting piece 4 in order to connect the fuel injection valve 1 by a common rail or directly to a high-pressure pump. Fuel may then be introduced through the fuel intake connecting piece 4 into an actuator chamber 5 provided in the interior of the valve housing 3, so that during operation of the fuel injection valve 1 fuel is situated in the actuator chamber 5, in which the piezoelectric actuator 2 is also provided.

The actuator chamber 5 is separated by a housing part 6 from a fuel chamber 7 that is likewise provided in the interior of the valve housing 3. In this housing part 6 through-openings 8, 9 are formed in order to convey into the fuel chamber 7 the fuel that has been conveyed through the fuel intake connecting piece 4 into the actuator chamber 5.

The valve housing 3 is connected to a valve seat body 10, on which a valve seat surface 11 is formed. The valve seat surface 11 interacts with a valve closing body 12 to produce a sealing seat. In this case, the valve closing body 12 is formed integrally with a valve needle 15, by which the valve closing body 12 is connected to a thrust plate 16 provided in the actuator chamber 5. The valve needle 15 extends through the housing part 6 along an axis 17 of the fuel injection valve 1. A spring element 18, which rests at one end against the housing part 6 and at the other end against the thrust plate 16, loads the piezoelectric actuator 2 with a biasing force, wherein by virtue of the loading moreover the valve needle 15 is actuated by means of the thrust plate 16, so that the sealing seat formed between the valve closing body 12 and the valve seat surface 11 is closed.

The valve housing 3 moreover has a connection element 20 to enable the connection of an incoming electric line to the fuel injection valve 1. The incoming electric line in this case may be connected by means of a plug-in connector to electric lines 21, 22. The electric lines 21, 22 are run through the housing 3 and an actuator foot 24, which is attached to an actuator body 23 of the actuator 2, to the actuator body 23. There is further attached to the

actuator body 23 of the piezoelectric actuator 2 an actuator head 25, via which the actuator body 23 acts counter to the force of the spring element 18 upon the thrust plate 16. The piezoelectric actuator 2 in the illustrated embodiment comprises the actuator body 23, the actuator foot 24 and the actuator head 25, so that an actuator module is formed.

The actuator body 23 of the piezoelectric actuator 2 comprises a plurality of ceramic layers 26, 27 and a plurality of electrode layers 28, 29 disposed between the ceramic layers 26, 27. Here, in order to simplify the representation only the ceramic layers 26, 27 and the electrode layers 28, 29 are denoted in Fig. 1. The electrode layers 28, 29 are connected alternately to the electric line 21 and the electric line 22 so that there are alternately positive and negative electrodes provided between the ceramic layers 26, 27.

Via the electric lines 21, 22 the piezoelectric actuator 2 may be charged, in which case it expands in the direction of the axis 17 so that the sealing seat formed between the valve closing body 12 and the valve seat surface 11 is opened. This leads to the injection of fuel from the fuel chamber 7 through an annular gap 30 and the open sealing seat. As the piezoelectric actuator 2 discharges, it contracts so that the sealing seat formed between the valve closing body 12 and the valve seat surface 11 is closed again.

The connection of the electric lines 21, 22 to the electrode layers 28, 29 may be effected by means of external electrode connections 35, 36. It is however

alternatively possible to provide internal electrode connections. The actuator body 23 is disposed between the actuator head 25 and the actuator foot 24.

The electrode connections 35, 36 are connected to the electrode layers 28, 29 by means of a soldered connection in the region of an external surface 37 of the actuator body 23. Solder is therefore provided on the external surface 37 of the actuator body 23. During the manufacture of the piezoelectric actuator 2 care has to be taken to ensure that damage to these soldered connections is extensively avoided in order not to impair the operating ability.

The piezoelectric actuator 2 may moreover have a protective sheath that guarantees protection against fuel provided in the actuator chamber 5. For the sake of simplicity, this protective sheath is not represented.

Fig. 2 shows a frequency- and amplitude characteristic of a trigger a.c. voltage during a variable frequency polarization operation to form domain structures in the ceramic layers 26, 27 of the actuator body 23 of the piezoelectric actuator 2 of the embodiment of the fuel injection valve 1. Here, in the top graph the time t is plotted on the abscissa and the frequency f in kilohertz is plotted on the ordinate. In the bottom graph, as in the top graph, the time t is plotted on the abscissa, while the amplitude U of the trigger voltage in volts is plotted on the ordinate. To illustrate the invention, in Fig. 2 three intervals T1, T2, T3 with regard to the time t are represented. In the first interval T1 the frequency f is set higher than 1 kHz and the amplitude U is set lower than

80 V. In the second interval the frequency f is set higher than 0.5 kHz and lower than 1 kHz, and the amplitude U is set higher than 100 V and lower than 200 V. In the third interval T3, the frequency f is set lower than 0.5 kHz and the amplitude is set higher than 200 V. Here it should be noted that in the transition region between the intervals T1, T2 and the intervals T2 and T3, which in each case succeed one another, transitions 38, 39 with regard to the frequency characteristic and transitions 38', 39' with regard to the amplitude characteristic occur, during which the actual values may differ from the set, and hence specified, values. The transitions 38, 39, 38', 39' are caused for example by specific capacitances and inductances.

In the first interval T1, as a result of a frequency of more than 1 kHz and an amplitude of less than 80 V of the trigger voltage, after a specific time a temperature of the actuator body 23 of for example 120°C is reached. At the same time, temperature regulation may additionally be effected by means of a fan. This allows rearrangement- and diffusion processes in a solder on the external surface 37 of the actuator body.

In the subsequent, second interval T2, the frequency is set lower than 1 kHz and the amplitude higher than 100 V. The second interval T2 is used in this embodiment as a short transition interval between the first interval T1 and the third interval T3.

In the third and crucial interval T3, which lasts at least 30 s, a polarization of the ceramic layers 26, 27 of the piezoelectric actuator 2 occurs. For this, preferably a

temperature of at least 150°C in the ceramic layers 26, 27 is specified. The frequency f in this case is set lower than 500 Hz, while for the amplitude U more than 200 V is specified.

The variable frequency polarization is used to align, i.e. polarize, domain structures inside the ceramic layers 26, 27 of the piezoelectric actuator 2 in such a way that, when during operation of the fuel injection valve 1 a voltage is applied, a defined deformation of the actuator 2 is achieved for the implementation of a desired lift of the valve needle 15. The frequency polarization in this case is deployed preferably at the end of the manufacturing chain of the actuator 2. To align the domain structures a minimum temperature in dependence upon the applied field intensity is required. This temperature is achieved by the self-heating of the actuator in that the actuator is triggered by positive a.c. voltage profiles in ramp form or trapezoidal form. If the minimum temperature is exceeded, for example by ca. 8°C, however, thermal damage may occur at a soldered connection and/or an enamel coating on the external surface 37 of the actuator body 23. A remedy for this may be provided by the temperature regulation for example by means of one or more fans.

Fig. 3 shows a simplified representation of the piezoelectric actuator 2 of the fuel injection valve 1 during manufacture. Electric lines 45, 46 connect the external electrode connections 35, 36 to a voltage source 47, the amplitude and frequency of which may be regulated. The trigger voltage supplied from the voltage source 47 is used to trigger the ceramic layers 26, 27 of the actuator body 23. This makes it possible to implement the variable

frequency polarization. The variable frequency polarization in this case is effected with a mechanical bias of the actuator body 23. For this purpose, the actuator body 23 is clamped between a thrust element 48 and a stationary seating plate 49. The thrust element 48 is then loaded with a biasing force F, thereby achieving a mechanical bias of the actuator body 23. The biasing force F in this case may be 200 N or more. By means of the biasing force F the formation of polarization cracks in the ceramic layers 26, 27 is advantageously influenced, thereby achieving a high degree of operating ability and reliability of the piezoelectric actuator 2 and hence of the fuel injection valve 1.

For the frequency polarization it is moreover advantageous if during the formation of the domain structures by the voltage source 47 a signal shape is specified, which corresponds to the operating conditions of the piezoelectric actuator 2 during operation of the fuel injection valve 1. The fatigue strength may thereby be increased. Variations of the desired valve lift of the valve needle 15 from the actual lift of the valve needle 15 that is provided by the triggering during operation may therefore be minimized.

The invention is not limited to the described embodiments.

Claims

1. Piezoelectric actuator (2), in particular an actuator for fuel injection valves, having an actuator body (23) that comprises a plurality of ceramic layers (26, 27) and a plurality of electrode layers (28, 29) disposed between the ceramic layers (26, 27),
characterized in
that domain structures in the ceramic layers (26, 27) are formed by variable frequency polarization.

2. Piezoelectric actuator according to claim 1,
characterized in
that the variable frequency polarization is effected in a plurality of intervals (T1, T2, T3), wherein upon a transition to a subsequent interval of the variable frequency polarization a frequency of a trigger voltage is reduced and/or an amplitude of the trigger voltage is increased.

3. Piezoelectric actuator according to claim 2,
characterized in
that upon a transition to a subsequent interval of the variable frequency polarization the frequency of the trigger voltage is reduced and at the same time an amplitude of the trigger voltage is increased.

4. Piezoelectric actuator according to one of claims 1 to 3,
characterized in
that the variable frequency polarization comprises a first interval (T1), a second interval (T2) provided chronologically after the first interval (T1), and at

least a third interval (T3) provided chronologically after the second interval (T2), that a frequency of a trigger a.c. voltage, by which the ceramic layers (26, 27) are triggered, and an amplitude of the trigger voltage in the first interval (T1) are set in such a way that a heating of the ceramic layers (26, 27) occurs to enable rearrangement- and diffusion processes in a solder provided on an external surface (37) of the actuator body (23), in the third interval (T3) are set in such a way that a polarization of the ceramic layers (26, 27) occurs, and in the second interval (T2) are set in such a way that intermediate values between the first interval (T1) and the third interval (T3) are assumed.

5. Piezoelectric actuator according to claim 4, characterized in
that in the first interval (T1) the frequency is higher than 1 kHz and the amplitude is lower than 80 V.

6. Piezoelectric actuator according to claim 4 or 5, characterized in
that in the second interval (T2) the frequency is higher than 0.5 kHz and lower than 1 kHz and the amplitude is higher than 100 V and lower than 200 V.

7. Piezoelectric actuator according to claim 4 or 6, characterized in
that in the third interval (T3) the frequency is lower than 0.5 kHz and the amplitude is higher than 200 V.

8. Piezoelectric actuator according to claim 7, characterized in

that a time length of the third interval (T3) is at least 30 s.

9. Piezoelectric actuator according to one of claims 1 to 8,
characterized in
that a signal shape of a trigger a.c. voltage for the variable frequency polarization is at least substantially trapezoidal.

10. Piezoelectric actuator according to one of claims 1 to 9,
characterized in
that the variable frequency polarization is effected with a mechanical bias of the actuator body (23).

11. Piezoelectric actuator according to claim 10,
characterized in
that the mechanical bias is applied by a biasing force (F) of at least 200 N.

12. Piezoelectric actuator according to one of claims 1 to 11,
characterized in
that at least during the variable frequency polarization temperature regulation is provided for the actuator body (23).

13. Fuel injection valve (1), in particular an injector for fuel injection systems of air-compressing, auto-ignition internal combustion engines, having a piezoelectric actuator (2) according to one of claims 1 to 12 and a valve closing body (12), which is actuable

by the actuator (2) and interacts with a valve seat surface (11) to form a sealing seat.

14. Method of manufacturing a piezoelectric actuator (2), which has an actuator body (23) comprising a plurality of ceramic layers (26, 27) and a plurality of electrode layers (28, 29) disposed between the ceramic layers (26, 27), wherein inside the ceramic layers (26, 27) domain structures are formed by variable frequency polarization.

15. Method of manufacturing a piezoelectric actuator, characterized in that at least during the variable frequency polarization temperature regulation is provided for the actuator body (23).

16. A piezoelectric actuator substantially as herein described with reference to the accompanying drawings.

17. A fuel injection valve substantially as herein described with reference to the accompanying drawings.

18. A method of manufacturing a piezoelectric actuator substantially as herein described.

Application No: GB0814433.9 **Examiner:** Peter Easterfield

Claims searched: 1 to 15 **Date of search:** 2 December 2008

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
A	-	WO 2005/081332 A1 (SIEMENS)
A	-	WO 2003/065468 A2 (SIEMENS)

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category	P	Document published on or after the declared priority date but before the filing date of this invention
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

F02M; H01L

The following online and other databases have been used in the preparation of this search report

WPI, EPODOC, TXTE

International Classification:

Subclass	Subgroup	Valid From
H01L	0041/24	01/01/2006
F02M	0051/06	01/01/2006
F02M	0059/46	01/01/2006
H01L	0041/083	01/01/2006