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(54) **Piezoelectric actuator for the operation of an injection pump for internal-combustion engines, and injector-pump assembly employing said actuator**

Piezoelektrisch Aktuator zur Steuerung einer Kraftstoffpumpe und Pumpe-Düse-Einheit

Actuateur piezo-électrique pour commander une pompe à carburant et un injecteur-pompe

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- **PATENT ABSTRACTS OF JAPAN vol. 1999, no. 12, 29 October 1999 (1999-10-29) & JP 11 182446 A (NISSAN MOTOR CO LTD), 6 July 1999 (1999-07-06)**
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Description

[0001] The present invention falls in the sector of fuel supply systems in internal combustion engines. More in particular, the present invention refers to a piezoelectric actuator for the operation of an injection pump of internal combustion engines and to the injector-pump assembly employing said actuator.

[0002] Supply systems are widely known, in particular for the supply of fuel injectors; they generally use controlled alternative pumps, also called vibrating pumps, which are based on the use of an actuator in the shape of a piston of ferromagnetic material controlled by an electromagnet supplied with alternate current. One of these pumps is described for example in patent MARELLI EP-0.953.764, which concerns, however, the oil supply in a two-stroke engine. Another example is described in US 6 079 636.

[0003] The present invention proposes to identify an injection system alternative to the ones already proposed, based on an actuator of a piezoelectric type, and such as to allow increased injectable flow rates per cycle, over known systems, given equal dimensions of the actuator and an improved reaction to high operation rpm. It is here reminded that three pump-injector systems are compared in the known art: with an actuator acting on a centrally-loaded membrane, or acting on an annular-load membrane, or piston pump-actuator systems.

[0004] It is evident from the results of the studies carried out on these systems that, in terms of deliverable fuel flow rate per stroke, in ideal conditions (perfectly uncompressible fluid, absence of blow-by, infinitely rigid container, ideal valves), the volume of injectable fluid, in the case of a piston pump-injector, may be obtained through the following mathematical expression:

$$\Delta V_{\mathbf{max}} = \frac{F_{zbf} \cdot \Delta L_0}{4 \cdot \Delta p} \qquad (1)$$

wherein ΔV_{max} = injectable fuel volume per cycle;
ΔL_0 = idle displacement of the actuator;
Δp = difference between injection pressure and supply pressure
F_{zbf} = load which may be developed by the actuator at the maximum voltage, locked between two non-yielding restraints (Zero Blocking Force)

[0005] By applying formula (1) to the case of piezoelectric actuators available on the market with a reference pressure of 75 bar, very modest volumes are obtained, as can be seen from the table of fig. 1, wherein:

- L is the length of the piezoelectric actuator,
- W is the actuator diameter
- F_{zbf} is the theoretical load which can be developed by the actuator,
- ΔL_0 is the idle actuator displacement,

whereas in the last column the displaced volumes are shown according to the type of piston actuator taken into consideration; it is immediately apparent that these volumes are insufficient, in the majority of cases, to supply even a 50 cc engine. An exception is only the actuator called EPCOS a which, in the embodiment showing two specimens arranged stacked (line 2 of the table of fig. 1), is sufficient for the power of a motorbicycle.

[0006] Due to obvious reasons of greater efficiency, but also for ease of description, here and in the following reference is always made to a piezoelectric-type actuator applied to a piston actuator, but it is intended that the teaching of the invention may be applied also to the other systems mentioned above.

[0007] The object of the present invention is hence to obtain an improvement of the performance of a piston pump-injector system with piezoelectric actuator, essentially by adopting means capable of amplifying the useful run of the piezoelectric actuator.

[0008] Such object is achieved by means of a structure of the piezoelectric actuator as defined in claim 1), as well as by an injection pump structure as defined in claim 4).

[0009] Further features and advantages of the invention will in any case be more evident from the following detailed description of a preferred embodiment, given purely by way of non-limiting example and shown in the accompanying drawings, wherein:

fig. 1 is a table showing, as already mentioned above, the data of some commercial types of piezoelectric actuators;
fig. 2 is a diagram showing the mechanical behaviour feature of a piezoelectric actuator;
fig. 3 diagrammatically shows, in an axial section, a piston pump-injector assembly with piezoelectric actuator according to the present invention;

fig. 4 shows in an extremely enlarged axial section a Belleville washer used in the device of fig. 3; and
fig. 5 shows a diagram of the operation feature of a Belleville washer, as it is used according to the invention.

[0010] As known, and as is evident from the diagram of fig. 2, a piezoelectric actuator has a linearly decreasing load/deformation feature. That is to say, at a set supply voltage (phantom lines for 0 V., for 80 V. and for 160 V., respectively), this type of actuator is capable of developing large loads with small piston displacements, but loses its thrust capability as the run increases, down to zero thrust when the maximum idle displacement is reached.

[0011] The diagram of fig. 2 is very easily interpreted: on the y axis the points idle operation are found, which represent the ideal case set forth earlier, wherein deformation is due only to the applied voltage (the maximum deformation value corresponding to the maximum supply voltage is commonly reported as the idle run of the actuator ΔL_o).

[0012] On the x axis, all the zero-deformation points are found; they represent an extreme situation referring to the non-ideal case, i.e. when the deformation imparted by the electrical control is fully neutralised by the elastic deformation. At the extreme point of the y axis, in correspondence of the maximum voltage, it is possible to guess that the corresponding electrical deformation (for the case set out in the drawing) at 60 μm at 160 V be neutralised by the elastic deformation equal to F/k, where F is the load and k is actuator rigidity.

[0013] As can again be guessed from the diagram of fig. 2, to the load of 1140 N a deformation of 60 μm, i.e. a rigidity of 19 N/μm, must correspond.

[0014] In intermediate situations between idle and zero-deformation, a progressive improvement of one performance is accomplished at the expense of the other, according to the linear law of fig. 2.

[0015] As can be easily guessed, the actual feature of the piezoelectric actuator does not perfectly suit the application thereof as a hydraulic pumping element, because the latter one requires the exertion of a constant force throughout the entire compression run. Instead, it has not been possible yet to use the full nominal run of the piezoelectric element, because, as seen with respect to the diagram of fig. 2, in the final part of the run the loading capability necessary to overcome fluid pressure would not be provided.

[0016] Since the piezoelectric actuator cannot exert a force which remains constant throughout the entire work run ΔL_o, it is provided, according to a first aspect of the present invention, to adopt a compromise between run and load, making use of a part only of the actual total work run. In other words, it is provided to use the piezoelectric element with an average run and an average load. It is possible to prove that this is the best solution, i.e. the one which allows to obtain the maximum work per cycle; as a matter of fact, in such solution the largest quantity of energy is delivered between the one available per work cycle.

[0017] The piezoelectric material of which commercial actuators are made further has the feature - common to all ceramic materials - of displaying an asymmetric mechanical behaviour in the presence of tensile and compressive stresses; in particular, tensile behaviour is poor, whereas the compressive one is acceptable for applications as actuator, both in static and in dynamic conditions.

[0018] In order to have a duration and reliability compatible with automotive industry requirements, it is hence imperative, in the light of what has been set forth above, that the actuators employed always work under a compressive stress. According to another aspect of the present invention, it is therefore provided to achieve this result by applying a preload to the piezoelectric element. Such technical practice allows to remarkably increase the useful life of the actuator.

[0019] From a functional point of view, the presence of a preload (assumed to be rigidly constant) does not affect the performance of the actuator, determining only a translation of the work cycle in the plane of fig. 2, i.e. bringing the work cycle inside the positive half-plane (compressive stress) of the load; thereby, a safety margin is accomplished which serves to safeguard the piezoelectric element from the dynamic tensile actions which are generated during fast operation and which must be neutralised precisely by the presence of the preload.

[0020] Should the preload be accomplished through a contrast spring, which is the simplest and cheapest solution, it must be noted, however, that when a contrast spring is added, the performance of a pump actuated by a piezoelectric actuator worsens as contrast spring rigidity increases.

[0021] According to an essential aspect of the present invention, however, it is suggested to adopt a negative-rigidity spring, i.e. a spring supplying a decreasing preload as deformation increases. An actuator deficiency is thereby countered by the special feature of the spring, i.e. the capability of providing high loads only at the beginning of the run.

[0022] In the case of the EPCOS actuator identified in line 3 of the table of fig. 1, if it is intended to work with a fixed preload of 500 N, with an idle displacement of 60 μm and a (fixed) load of 1140 N, only 50% of the run can be exploited. However, if, according to the present invention, a spring having a rigidity for example of -9,5 N/μm is used, which is capable of giving an initial-run load of 900 N and a final-run load of

$$900\ N - 9{,}5\ N/\mu m \times 60\ \mu m = 330\ N$$

it was possible to ascertain that the load loss which may be developed by the actuator is compensated by the spring feature, and 100% of the run can be exploited, thereby doubling performance.

[0023] Among the springs widespread in the technical practice, the ones capable of displaying a negative rigidity are conical disc springs, or so-called Belleville washers (see fig. 4). In this kind of springs, upon varying of the ratio η between the free height h of the conical disc and its thickness t, different curve trends are obtained; the diagram of fig. 5 shows an example, wherein:

- if η < 1.41, the load increases in the deformation direction,
- if <1.41 η < 2.83, there is a deformation area, around the free height value, where the load decreases (negative rigidity);
- if η > 2.83 the previous behaviour is heightened and even a load sign inversion is obtained (the spring pulls instead of pushing and, if it is not constrained, jumps into a stable position with higher deformation values).

[0024] The most suitable behaviour for the application of the present invention is evidently the one where 1.41 < η < 2,83.

[0025] However, the embodiment comprising springs having a negative rigidity of -9.5 N/μm, although theoretically possible, is of no practical usefulness. As a matter of fact, in order to obtain a similar value of the diagram gradient of fig. 2, albeit limited to the middle portion where the derivative takes up the absolute minimum value, it would be necessary to resort to diameters of 800 mm with thicknesses of 20 mm. These dimensions are evidently not admissible for use in internal combustion engines, in particular those intended for motor bicycles. The problem has therefore arisen of how to manufacture a spring featuring maximum negative rigidity with the smallest dimensions.

[0026] According to another important aspect of the present invention, it was therefore resorted to the idea of artificially amplifying the negative rigidity of the spring, arranging two springs in series and precisely one negative-rigidity spring coupled with a positive-rigidity spring. It is known that the overall rigidity of two springs arranged in series is given by the formula:

$$k = \frac{k_1 \cdot k_2}{k_1 + k_2}$$

(which among other things is confirmed by the fact that, when two conventional springs are placed in series, rigidity decreases: for example, assuming that k_1 = 100 and k_2 = 100, the result is k = 50). If, however, according to the present invention, a negative-rigidity spring is arranged in series with a positive-rigidity spring, as mentioned, an overall negative rigidity is obtained, but amplified in its modulus. For example, assuming k_1 = 100 and k_2 = -95, the result becomes k = 1900).

[0027] On the basis of such a configuration, it is hence possible to design a spring capable of providing maximum negative rigidity with respect to material resistance, having dimensions compatible with its application in internal combustion engines. As a result of this dimensioning, a spring having the following measures is for example manufactured (see the references of fig. 4) :

D = 28 mm
d = 16 mm
h = 1.3 mm
t = 0.5 mm
h/t = 2.6
k_{min} = -0.56 N/μm
phosphate-containing steel material 1.1248 C75S(Ck75)
wherein a high ratio between the spring height h and the thickness t of the spring disc is highlighted.

[0028] The rigidity thus obtained for the spring dimensioned as above is then doubled with two springs arranged packetwise and further amplified arranging in series a conventional spring with a rigidity of 1,15 N/μm.

[0029] From the calculations carried out, it appeared that a piezoelectric pump-injector, particularly suited to small-powered internal combustion engines - having for example a swept volume of 50 cm^3 - can be manufactured, according to the present invention, also employing a small, inexpensive piezoelectric element such as the Epcos one (table of fig. 1), in association with a preload spring having a negative rigidity whose modulus is about half that of the piezoelectric element.

[0030] It is intended, however, that the invention is not to be considered limited to the particular arrangement illustrated above, which represents only an exemplary embodiment thereof, but that several changes are possible, all within the reach of a person skilled in the field, without departing from the scope of protection of the invention, as defined in the following claims.

Claims

1. Piezoelectric actuator for the actuation of an injection pump for internal combustion engines, comprising in combination a piezoelectric element and a contrast spring consisting of at least a Belleville washer, wherein said contrast spring comprises at least one Belleville washer having negative rigidity, i.e. providing a decreasing force as deformation increases, and sized so that the ratio between the spring height h and the thickness t of the Belleville washer disc is in the range

$$1.41 < h/t < 2.83$$

and **characterised in that** at least a conventional, positive-rigidity spring, is arranged in series with said Belleville washer, said contrast spring supplying a preload of the piezoelectric element.

2. Piezoelectric actuator as claimed in claim 1), **characterised in that** said Belleville washer has a negative rigidity whose modulus is about half the rigidity of the piezoelectric element.

3. Piezoelectric actuator as in claim 1), **characterised in that** it comprises a pack of three identical negative-rigidity Belleville washers, arranged in parallel with each other and in series with at least a conventional, positive- rigidity spring.

4. Injection pump for internal combustion engines, in particular small-powered ones, **characterised in that** it comprises an actuator as in any one of the preceding claims in combination with a piston pump-injector.

Patentansprüche

1. Piezoelektrische Betätigungseinrichtung für die Betätigung einer Einspritzpumpe für Verbrennungskraftmotoren, umfassend in Kombination ein piezoelektrisches Element und eine Gegendruckfeder, die aus zumindest einer Belleville-Scheibe besteht, wobei die genannte Gegendruckfeder zumindest eine Belleville-Scheibe mit negativer Steifigkeit aufweist, d.h. die eine mit zunehmender Verformung abnehmende Kraft bereitstellt, und die so bemessen ist, dass das Verhältnis zwischen der Federhöhe h und der Dicke t der Belleville-Scheibenfeder in dem Bereich $1.41 < h/t < 2.83$ liegt, und **dadurch gekennzeichnet, dass** zumindest eine herkömmliche, eine positive Steifigkeit aufweisende Feder in Reihe mit der genannten Belleville-Scheibe angeordnet ist, wobei die genannte Gegendruckfeder eine Vorspannung des piezoelektrischen Elements liefert.

2. Piezoelektrische Betätigungseinrichtung nach Anspruch 1, **dadurch gekennzeichnet, dass** die genannte Belleville-Scheibe eine negative Steifigkeit aufweist, deren Modul etwa die Hälfte der Steifigkeit des piezoelektrischen Elements beträgt.

3. Piezoelektrische Betätigungseinrichtung nach Anspruch 1, **dadurch gekennzeichnet, dass** sie ein Paket von drei identischen Belleville-Scheiben mit negativer Steifigkeit umfasst, die parallel zueinander und in Reihe mit zumindest einer herkömmlichen, eine positive Steifigkeit aufweisenden Feder angeordnet sind.

4. Einspritzpumpe für Verbrennungskraftmaschinen, insbesondere mit kleiner Leistung, **dadurch gekennzeichnet, dass** sie eine Betätigungseinrichtung nach einem der vorangehenden Ansprüche aufweist, in Kombination mit einer Kolbenpumpen-Einspritzvorrichtung.

Revendications

1. Actionneur piézoélectrique pour l'actionnement d'une pompe à injection pour moteurs à combustion interne, comprenant, en combinaison, un élément piézoélectrique et un ressort de contraste consistant en au moins une rondelle Belleville, dans lequel ledit ressort de contraste comprend au moins une rondelle Belleville ayant une rigidité négative, c'est-à-dire offrant une force décroissante tandis que la déformation augmente, et dimensionnée de manière que le rapport entre la hauteur de ressort h et l'épaisseur t du disque de rondelle Belleville se trouve dans la plage

$$1,41 < h/t < 2,83$$

et **caractérisé en ce qu'**au moins un ressort à rigidité positive, classique, est agencé en série avec ladite rondelle Belleville, ledit ressort de contraste fournissant une précharge de l'élément piézoélectrique.

2. Actionneur piézoélectrique selon la revendication 1, **caractérisé en ce que** ladite rondelle Belleville a une rigidité négative dont le module est d'environ la moitié de la rigidité de l'élément piézoélectrique.

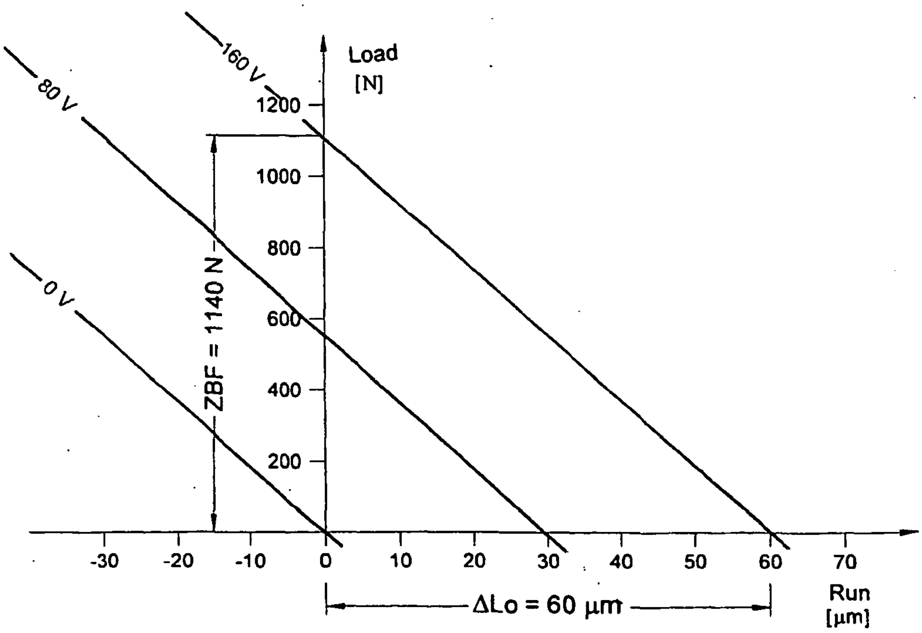
3. Actionneur piézoélectrique selon la revendication 1, **caractérisé en ce qu'**il comprend un ensemble de trois rondelles Belleville à rigidité négative identiques, agencées en parallèle les unes aux autres et en série avec au moins un ressort à rigidité positive, classique.

4. Pompe à injection pour moteurs à combustion interne, en particulier de faible puissance, **caractérisée en ce qu'**elle comprend un actionneur selon l'une quelconque des revendications précédentes en combinaison avec un injecteur-pompe à piston.

Fig. 1

Type	*L*	*W*	F_{zbf}	*ΔLo*	*Injectable volume*
	mm	mm	N	µm	mm^3
EPCOS a	30	6,8	1980	40	2,64
2x(EPCOS a)	60	6,8	1980	80	**5,28**
EPCOS b	45	5,2	1140	60	2,28
PI P 802.10	18	5	1500	15	0,75
2x(PI P 802.10)	36	5	1500	30	1,50
3x(PI P 802.10)	54	5	1500	45	2,25

Fig. 2



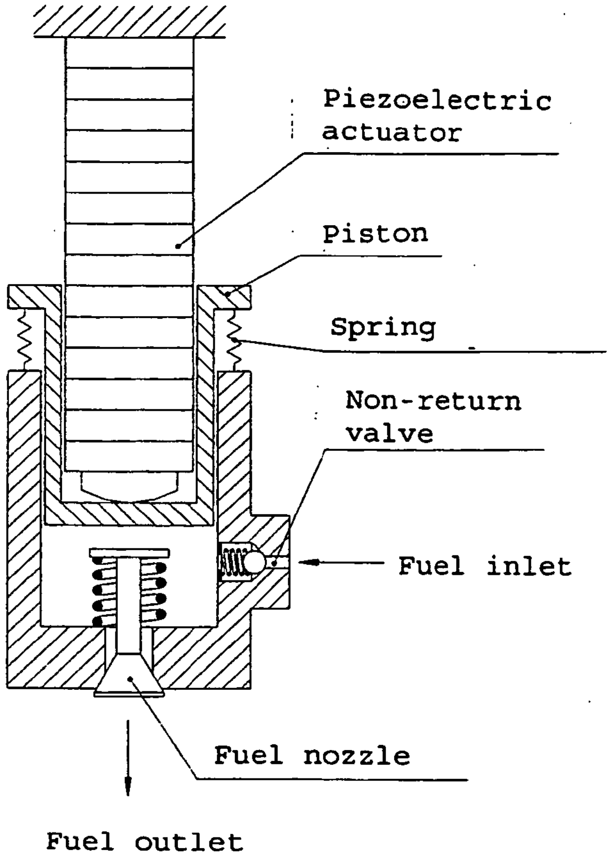

Piezoelectric actuator
Piston
Spring
Non-return valve
Fuel inlet
Fuel nozzle
Fuel outlet

Fig. 3

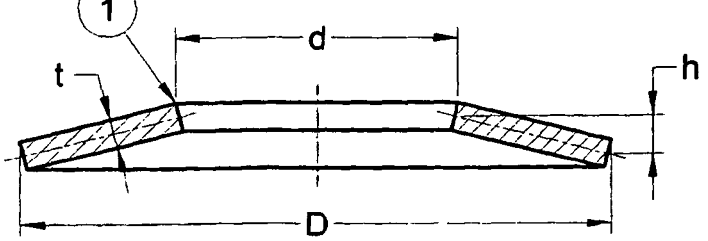
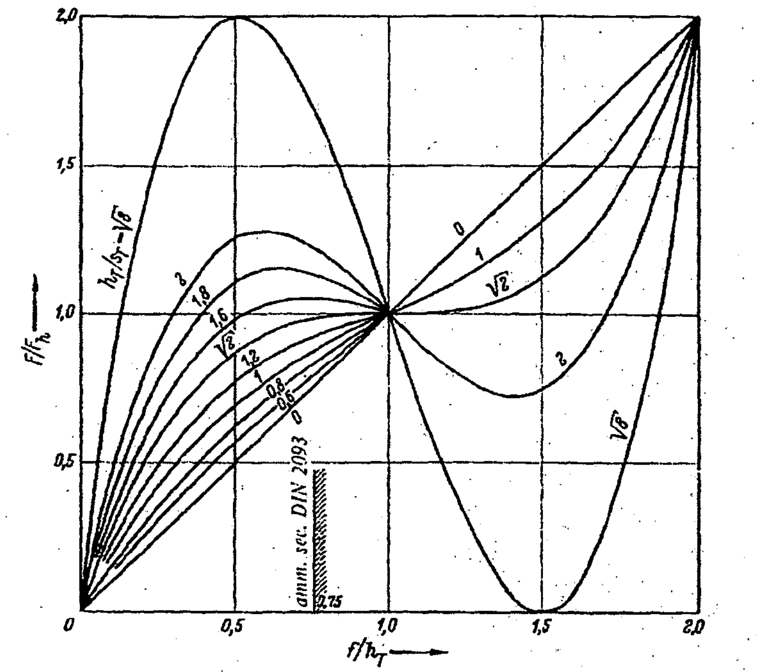


Fig. 4

Fig. 5



REFERENCES CITED IN THE DESCRIPTION

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