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(54) Electromagnetic ultraswift actuator without springs

(57) Electromagnetic ultraswift actuator without springs including a movable part (1) and a statoric element (7) coaxial to the movable part (1), being the movable part (1) free to axially move inside the statoric element (7) , a permanent magnet (5) having its magnetic poles (6) following each other along the longitudinal axis of the movable part (1), being the movable part (1) kept in a provided position through the magnetic field generated by the permanent magnet (5) and suitable stroke limiters (2, 3, 12, 13, 14, 16), and a statoric winding (9) coaxial to the permanent magnet (5) and excitable so that it interacts with the permanent magnet (5) magnetic field, characterized in that the magnetic field generated in the winding (9) excites the statoric part (7) polarizing it so that the permanent magnet (5) reacts together with the movable part (1) connected to it moving towards another provided position, so that the axial translation of the permanent magnet (5) and consequently of the movable part (1) is respectively caused:

- in one direction, just by spontaneous attraction (active magnet/passive ferromagnetic circuit) eventually reinforced through an auxiliary electromagnetic excitation.
- in the opposite direction, substantially by repulsion between polarities (active magnet/ active electromagnetic circuit) having the same sign.

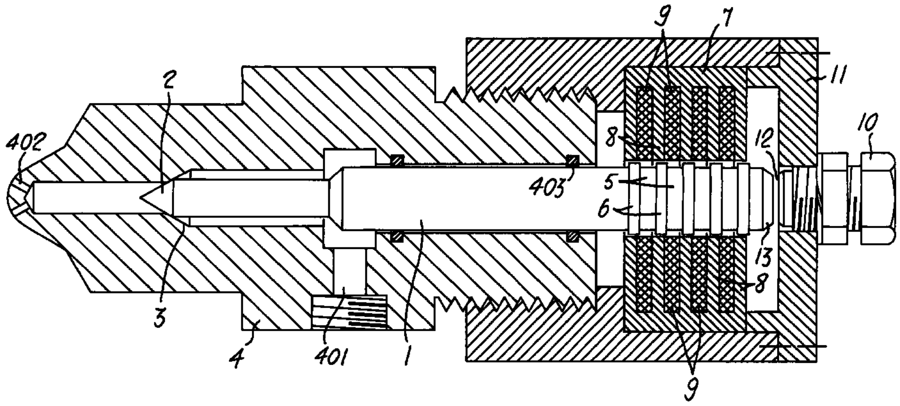

Fig. 1

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Description

[0001] The present invention refers to electromagnetic actuators and in particular the linear and/or tangential electromagnetic actuators used to control drivers in hydraulic, pneumatic, oleodynamic servomechanisms; to control positioning mechanical devices through transmissions or other devices fitted to ensure the repetitiveness of the obtained movement; to make physical quantities measurement devices or for fuel injection valves in the combustion engines, and moreover without mechanical parts returning spring, such as spiral springs or others.

[0002] Usually in the field of utilization of such actuators for valves, the required stroke of the movable part connected to the shutter to make the opening and the closing of the admitting ports is very short (for example some tenth of millimeters), but it has to be made in a very short time, with strong contrast strengths and in very unfavorable functioning environmental conditions, such as for instance the fuel injection into an engine or the driving of high pressure hydraulic servosystems where the functioning of the different parts of the valve have to be realized also in presence of the fluid. For security reason, above all in this last case, the actuator must always ensure the closing position of the valve shutter even in case of lack of electric power or fault.

[0003] Such actuators are known in the field, for instance the patent DE 3501193 describes a combustion engine injection valve having a ferromagnetic core excited through a winding operating on an armature which acts as a closing part. The armature is a permanent magnet and moves towards the core just when the winding is not excited by current so that the closing part closes the seat. The excited winding generates a magnetic field opposing the permanent field contrasting it until the fluid pressure succeed in opening the valve.

[0004] This known electromagnetic actuator works, when closing, according to the natural tendency of a movable part, in this case a permanent magnet, of a magnetic circuit to move towards a certain position in search of the minimum reluctance conditions through the aligning of the generated flow lines; it is to say that in a first stage the permanent magnet is attracted by a ferromagnetic core so to reduce to the minimum the air distance from it, that is the air gap. Then, in a second stage, the electric excitation of the winding generates a magnetic field able to oppose the magnet permanent field and which works through the ferromagnetic core in a way to clear its attraction strength allowing the fluid pressure to open the valve without the active contribution of the electromagnet strength. Naturally the initial position of the permanent magnet as to the electromagnetic circuit has to be "favorable" to allow displacement, and this statement will hereafter explained in detail.

[0005] This known electromagnetic actuator has nevertheless some disadvantages, first of all the fact that in the applications providing the use of such an actuator, such as the fuel injection into engines, are required high response speeds of the movable part even to the electric excitation, and consequently considerable bi-directional strengths joined with high induction values, and besides that particularly in the use of such actuators in hydraulic servosystems, the shutter connected to such movable part has to ensure, for security reason, a good closing strength in case of lack of electric power or faults. For these reasons it is necessary to lighten the mass of the movable part which has to be optimized to be substantially reduced in its dimensions and take, moreover, a fluid dynamic shape according to such high moving speeds in condition of immersion.

[0006] A particularly important disadvantage for the actuators using spring returning means, moreover, is the necessity to make a careful dimensioning of its spring parts which have to ensure high response speeds without causing phenomena inducted through the resonance frequencies typical of such parts.

[0007] Aim of the present invention is therefore to overcome the disadvantages of the known technique by means of an electromagnetic ultraswift Actuator without springs including a movable part and a statoric element coaxial to the movable part, being the movable part free to axially move inside the statoric element, a permanent magnet having its magnetic poles following each other along the longitudinal axis of the movable part, being the movable part kept in a provided position through the magnetic field generated by the permanent magnet and suitable stroke limiters, and a statoric winding coaxial to the permanent magnet and excitable so that it interacts with the permanent magnet magnetic field, characterized in that the magnetic field generated in the winding excites the statoric part polarizing it so that the permanent magnet reacts together with the movable part connected to it moving towards another provided position, so that the axial translation of the permanent magnet and consequently of the movable part is respectively caused:

- in one direction, just by spontaneous attraction (active magnet/passive ferromagnetic circuit) eventually reinforced through an auxiliary electromagnetic excitation.
- in the opposite direction, substantially by repulsion between polarity (active magnet/active electromagnetic circuit) having the same sign.

[0008] According to one aspect of the present invention the permanent magnet works, when the winding is excited, preferably in correspondence of its maximum energy product, reducing the movable masses and then advantageously accelerating the actuator.

[0009] Moreover, according to another aspect of the present invention, the actuator includes a plurality of permanent magnets coaxial to the movable part and having their magnetic poles following each other along the longitudinal axis of the movable part, and several coils coaxially set following each other on the statoric part and in a way such that when excited each field pole activated by the magnetic fields inducted by the coils in the statoric part interacts with at least one pole of such permanent magnets to cause an axial shifting of the movable part from one of these provided positions.

[0010] One of such provided positions can be for example the closing position of a fuel injection valve in the engines, and will be ensured though the closing of the magnetic circuit of the permanent magnets towards the field poles of the statoric part with its coils not excited by current or, alternatively, excited in a way to reinforce this closing action, thus through an induced field increasing the field of the permanent magnet. As said before it is necessary that the permanent magnet is in favorable position for the following stage of the valve opening caused by the excitation of the coils which induces on the statoric part field poles a field opposing that of the permanent magnet, thus that it is not in the condition of minimum reluctance as to the statoric part, and this is ensured by the stopping of the shutter against its seat suitably dimensioned according to the valve stroke one want to have. In this case the axial translation of the movable part means therefore the opening of the injection valve.

[0011] According to one aspect of the present invention the coils winded around the actuator statoric part will be positioned at a distance such that each field pole comprised between two coils coaxially following and fed with opposite running currents, forms a single induced magnetic pole interacting with at least one of the magnetic poles of the permanent magnets on the movable part, which have very thin polar ends or poles working as flow concentrator so to generate remarkable strengths: a) closing strength, in case the coils are excited so to generate a magnetic field increasing the one of the permanent magnet; b) opening strength, in case the coils field opposes the one of the magnet.

[0012] In fact, as known, the electromagnetic strength generated in a movable part of a magnetic circuit is proportional to the linked surfaces and to the square of the induction; moreover through a suitably dimensioning of the permanent magnets poles and the coils winded around the statoric part, the induced currents are notably reduced in the movable part advantageously for the response time for that part and of the axial movement speeds, such an advantage is even greater if it is provided the use of an even number of such coils winded around the statoric part. The nearer coils moreover allow, as known, the reduction of the reciprocal inductance between themselves and of the flows dispersed in the statoric part, with a resulting increase of the response speed and an improvement in the actuator efficiency.

[0013] According to what has been said is then advantageous to use permanent magnets characterized by remarkable energy products (and, in this case, not demagnetizable) combined with mild magnetic materials in the statoric part suitable for uses with steep front current pulses with very high induction values, as said before.

[0014] The efficiency and the stability of the device used by the present invention allow, with limited energy absorptions, to get the margins necessary to oppose the effects of great changes of temperature and eventual changes of the stroke caused by possible plastic deformations of the structure caused by the strong pressures acting within the circuit of an hydraulic servomechanism.

[0015] Further advantages of the actuator of the present invention will be better understood from the following description of a preferred operating form applied to an injection valve of a fluid, such as fuel in combustion engines, to be regarded as an example not limitative in any way and referred to the enclosed drawings, where:

- Fig. 1 shows a sectional view of an operative form preferred of the actuator of the present invention applied to an injection valve of fuel or another fluid, in closing position;
- Fig. 2 shows a sectional view of the valve of Fig. 1 in opening position.
- Fig. 3 shows a partly sectioned view in an operative variation form of the valve of Fig. 1 and 2 for the opening position; and
- Fig. 4a and 4b shows schematic diagrams where it can be seen the course of the magnetic and electromagnetic forces on the movable part or valve stem according to the moving of said stem.

[0016] With reference to Fig. 1 it is shown the electromagnetic actuator of the present invention applied to a fluid injection valve shown in closing position and consisting of a cylindrical movable part 1 including a shutter 2 abutting against a suitable seat 3 of the valve to prevent the fluid, for instance fuel, coming into the body 4 of the valve through the inlet 401, from reaching the feeding holes 402. As one can notice said valve has a modular structure so that it can be assembled and disassembled by separating from each other the several parts of which it consists. Coaxially to the valve movable part 1 and connected to it are a succession of permanent magnets 5 (4 in this case) having their concentrated magnetic poles 6 coaxially placed along such part and with alternate polarities (for instance North-South-North-South-North). Coaxially to the movable part 1 it is shown a cylindrical statoric part 7 advantageously made, as said before, of suitable mild magnetic materials (within which the movable part 1 is evidently free to move) suitably shaped so that it forms field poles 8 around which are coaxially winded coils 9, which advantageously in this figure are in an even number (and 4 precisely) to reduce, during their electric excitation, the reciprocal inductance and the flows dispersed in the statoric part 7.

[0017] Going on with the description of the valve it can be moreover noticed a screw stroke limiter 10 on the valve closing lid 11, the lower surface 12 of said screw stroke limiter 10 is the ledge or stop, in case of opening of the valve, for the movable part end 13, and later on it will be explained the importance of such stroke limiter. In such valve there could be sealing rings 403 to avoid a return of the fluid fed into it through the inlet 4 towards the electromagnetic actuator. The closing position of the shutter 2 on the seat 3 is ensured in this operative form by the position of the poles 6 of the permanent magnets 5 as to the field poles 8 of the statoric part, that is to say starting from the left side of the movable part 1 and considering for instance the first magnetic pole 6, which is for instance supposed to be North, the magnetic field generated by the permanent magnet 5 which includes such pole 6 will tend to force it towards the first field pole 8 of the statoric part 7, which for the first hypothesis it is supposed not to be polarized since the coils 9 are not fed by any current, such pole 6 would tend to the minimum reluctance conditions, that is to say that it would move to align the flow lines of the magnet 5 to which it is connected with the corresponding field pole 8, not excited, but the stop of the shutter 2 against the seat 3 advantageously prevents this aligning from completing, so there will be a force which tends to push each magnetic pole 6 towards its respective field pole, and such force will be, within the saturation limit of the magnetic materials, as greater as smaller are the side surfaces of the magnetic poles 6 and therefore as more the flow is concentrated.

[0018] The functioning of the actuator of the present invention will be further explained by looking at Fig. 2 together with Fig. 1. Taking again what has been said for the preceding figure the shutter closing is ensured by the magnetic strength generated by the permanent magnets 5 through their polarities 6, because such magnets are not, thanks to a suitable stroke limiter (shutter 2 - seat 3), in the condition of minimum reluctance. Then to open the valve it is necessary to excite the coils 9 so that in their field poles 8 are inducted polarities opposing the magnetic field generated by the permanent magnets 5 and concentrated in the poles 6, and this, since the setting of the magnetic poles 6 on the longitudinal axis of the movable part 1, can be done just by feeding the coils 9 one after the other with currents circulating within in the opposite direction, so, considering again the first pole 6 from the left which is supposed to be a North one, it will be necessary to feed the first coil 9 with a current inducting a magnetic field such that it produces in the first field pole 8 an induced North pole pushing back to the right the pole 6 and then the movable part which, as in the preceding closing case, will have an abutment end 13 against the lower surface 12 of the screw stroke limiter 10. From the figure it emerges that such stopping of the end 13 against the surface 12 prevents the magnetic poles 6 from reaching the zero strength conditions and moreover it allows to change the stroke during the opening by adjusting the screwing of the screw stroke limiter 10 on its lid 11. The effect of pushing and so of translation speed of the part 1 will be advantageously multiplied for the number of the magnetic poles 6 and corresponding field poles 8, ensuring very short opening and closing times and high efficiency of the actuator, because, being the coils 9 as near as possible, its shape is extremely compact with the consequent energy advantages and of reduction of the previously mentioned dispersed flows.

[0019] The stroke limiter during the opening (end 13 of the movable part 1 - lower surface 12 of the screw stroke limiter 10) can be replaced, according to an operative variation form of the present invention reported in Fig. 3, by an adjustment flange 14 provided with suitable fastening screws 15 to the valve body and so disconnectable and interchangeable with another one, which serves as stroke limiter during the opening for the movable part 1 suitably shaped so to have an annular part 16 ensuring the abutment against the adjustment flange 14. As on can notice the valve lid 11 in this operative variation form is continuous and not perforated since it has not to house any stroke limiter or provide any abutment for the movable part 1. The functioning of the actuator is unchanged as to what described before.

[0020] Fig. 4a and 4b explain better the functioning of the actuator of the present invention.

[0021] Taking into consideration first the plot of Fig. 4a showing on the abscissa axis the shifting S of the poles 6 and on the ordinate axis the magnetic strength F generated by the permanent magnets 5 and the electromagnetic strength F_1 generated by the coils 9, the first magnetic pole 6 taken into account as example in the description of the preceding figures, will be, without electric excitation of the coils 9 in the position C (it is to say closed valve), as one can notice it is not in the condition of minimum reluctance corresponding to the position indicated with 0, that is to say the condition where the lines of the magnetic field of the permanent magnet 5 to which it belongs are axially aligned with the field pole 8 by which it is attracted, and this thanks to the stopping of the shutter 2 against the valve seat 3. To shift the pole 6 from position C and so the movable part 1 it is necessary to provide for an electromagnetic strength F_1 able to oppose the strength F, constant in time, of the magnet 5 and then, reversing it, to push the movable part towards the opening position A_1 making it to do the shifting C_1A_1, where A_1, like C, the permanent magnet will be far from the condition of minimum reluctance, this is position 0. The same way, to move the movable part 1 from the opening position back to the closing position C it will be sufficient to deactivate the coils 9. In this particular case the excitation provided by the coils to open the valve (shifting C_1A_1) is provided so to cause a shifting of the movable part 1 which occurs at the same speed, and so in the same time, of the closing shifting AC, in fact the curves F and F_1 are symmetrical to the S axis of the shifting. It is also to notice that the shifting AC and C_1A_1 are advantageously carried out in correspondence of the crests of the curves F and F_1 so to work always with great values for such strengths and so very short moving times. If one wishes to change the stroke AC and so the C_1A_1 by flattening the curve in correspondence of its crest it is possible according to the invention to suitably shape the field poles 8 and at the same time or alternatively adopt a so-called vernier disposition.

[0022] In Fig. 4b is shown a variation of the functioning of the actuator of the present invention, that is to say the case where the magnetic poles 6 of the permanent magnets 5 not only tend naturally to the field poles 8 deactivated during the closing stage, but also are attracted by them through an auxiliary electromagnetic strength F_2 with the same sign; this means that in the previous case the first magnetic pole 6 of Fig. 1, supposed to be North, was attracted by the first not polarized field pole 8, in this case the first coil 9 of the statoric part 7 will be instead excited to induce in the first field pole 8 a magnetic field having South polarity so to attract the permanent magnet 5 with a strength F_2 greater than the strength F of Fig. 4a, and consequently to make a much more quick closing of the valve. Naturally, in case of emergency, as lack of electric power or fault, the only strength able to ensure the closing of the valve shutter 3 is the F one of the case of Fig. 4a. As one can notice the shifting A_2C_2 of the closing stage is equal to the shifting AC of the previous functioning, but it occurs at an higher speed, while the opening stage $C_{21}A_{21}$ ($=C_1A_1$) remains unchanged both for what concerning the intensity of the strengths in play and for what concerning the shifting of the movable part.

[0023] On the basis of what has been stated in the previous description it is possible to sum up the advantages provided by the actuator of the present invention in the following points:

- the absence of return springs of the movable part 1 eliminates the phenomena inducted by the resonance frequencies characteristic of such spring means and the effects of degradation, of the wears and of the damages of these last ones.
- the values of the strengths in play can be adjusted and their direction can be reverted through the reciprocal axial sliding of the active parts (movable parts 5 and 6 as to the statoric parts 8 and 9) until reaching the desired effect.
- the modular assembling of the actuator allows, using standard basic components (permanent magnets 5, their magnetic poles 6 and coils 9) to obtain with the same model an unusual extension of the strengths range (even > 10);
- the ratio between the closing (F or F_2) and opening (F_1) strengths, the absolute values of the strength as to the shifting, can be easily checked and adapted to the requirements of particular applications through a suitable dimensioning of the actuator of the present invention;
- the intrinsic flexibility of the actuator can be further increased by using special shapes of the field poles 8, together or alternatively to the vernier configurations as to the magnetic poles 6 of the permanent magnets 5;
- sophisticated checks of the electric feeding of the coils 9 allow a control of the strengths in play in the actuator of the present invention according to highly personalized schema.

Claims

1. Electromagnetic ultraswift actuator without springs including a movable part (1) and a statoric element (7) coaxial to the movable part (1), being said movable part (1) free to axially move inside said statoric element (7), a permanent magnet (5) having its magnetic poles (6) following each other along the longitudinal axis of the movable part (1), being the movable part (1) kept in a provided position through the magnetic field generated by the permanent magnet (5) and suitable stroke limiters (2, 3, 12, 13, 14, 16), and a statoric winding (9) coaxial to the permanent magnet (5) and excitable so that it interacts with the permanent magnet (5) magnetic field,

   characterized in that the magnetic field generated by the winding (9) excites the statoric part (7) polarizing it so that the permanent magnet (5) reacts together with the movable part (1) connected to it moving towards another provided position, so that the axial translation of the permanent magnet (5) and then of the movable part (1) is respectively caused:

   - in one direction, just by spontaneous attraction (active magnet/ passive ferromagnetic circuit) eventually reinforced through an auxiliary electromagnetic excitation;
   - in the opposite direction, substantially by repulsion between polarity (active magnet/ active electromagnetic circuit) having the same sign.

2. Electromagnetic ultraswift actuator without springs according to claim 1, characterized in that the permanent magnet (5) works, when the statoric winding (9) is excited, preferably in connection with its maximum energy production.

3. Electromagnetic ultraswift actuator without springs according to claim 1, characterized in that it includes several permanent magnets (5) coaxial to said movable part (1) and having their magnetic poles (6) following each other along the longitudinal axis of said movable part (1), and a plurality of coils (9) coaxially set following each other on said statoric part (7) and in a way such that once excited each field pole (8) activated by the magnetic fields

inducted by said coils (9) in said statoric part (7) interacts with at least one pole (6) of said permanent magnets (5) to cause an axial shifting of said movable part (1) from one of these provided positions.

4. Electromagnetic ultraswift actuator without springs according to claim 1, characterized in that said coils (9) coaxially following each other on said statoric part (7) are positioned at a distance such that each of said field poles (8) comprised between two coaxially following coils (9) forms a single magnetic pole (8) interacting with at least one of said magnetic poles (6) of the permanent magnets (5).

5. Electromagnetic ultraswift actuator without springs according to claims 1 and 2, characterized in that in any couple formed by two following coils (9) of said coils coaxially following each other the feeding currents of said two following coils (9) circulate in opposite directions.

6. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that said distance between each of said coils (9) is such that said magnetic fields induced by said coils (9) link one another so to remarkably reduce the currents induced into said movable part (1).

7. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that, said coils (9) are in an even number so to advantageously reduce the reciprocal inductance in said statoric part (7).

8. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that, the magnetic poles (6) of said permanent magnets (5) are dimensioned in order to advantageously concentrate the magnetic field generated by said permanent magnet (5).

9. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that, the magnetic poles (6) of said permanent magnets (5) radially project from the body of the permanent magnet (5).

10. Electromagnetic ultraswift actuator without springs according to of the preceding claims, characterized in that, one of the said suitable stroke limiters (2, 3, 12, 13, 14, 16) is provided by the stopping of a shutter (3) included in said movable part (1) against a seat (3) of said actuator.

11. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that, one of the said suitable stroke limiters (2, 3, 12, 13, 14, 16) is provided by the stopping of the end (13) of said movable part (1) against the lower surface (12) of an adjustable screw stroke limiters (10) on the closing lid (11) of said actuator.

12. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that, its assembling procedure is modular.

13. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that, on of said stroke limiters (2, 3, 12, 13, 14, 16) is an adjusting flange (14) coaxial to said movable part (1).

14. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that, said adjusting flange (14) is provided with fastening screws (15) and so it is disconnectable from said actuator and replaceable with another one.

15. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that, said statoric field poles (8) can be suitable shaped to increase the flexibility of said actuator.

16. Electromagnetic ultraswift actuator without springs according to any of the preceding claims, characterized in that, in said actuator on can adopt a vernier configuration of said statoric field poles (8) as to the said magnetic poles (6) of said permanent magnets (5).

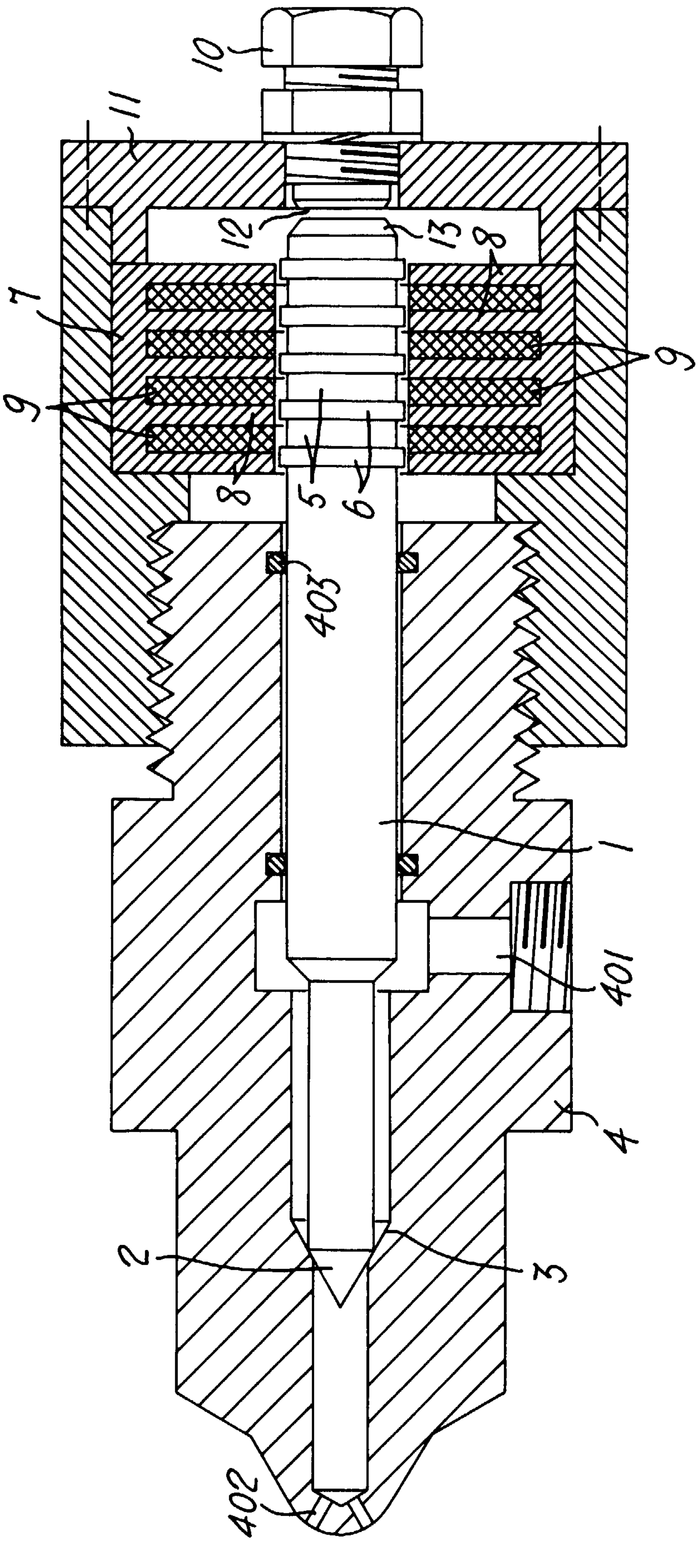

Fig. 1

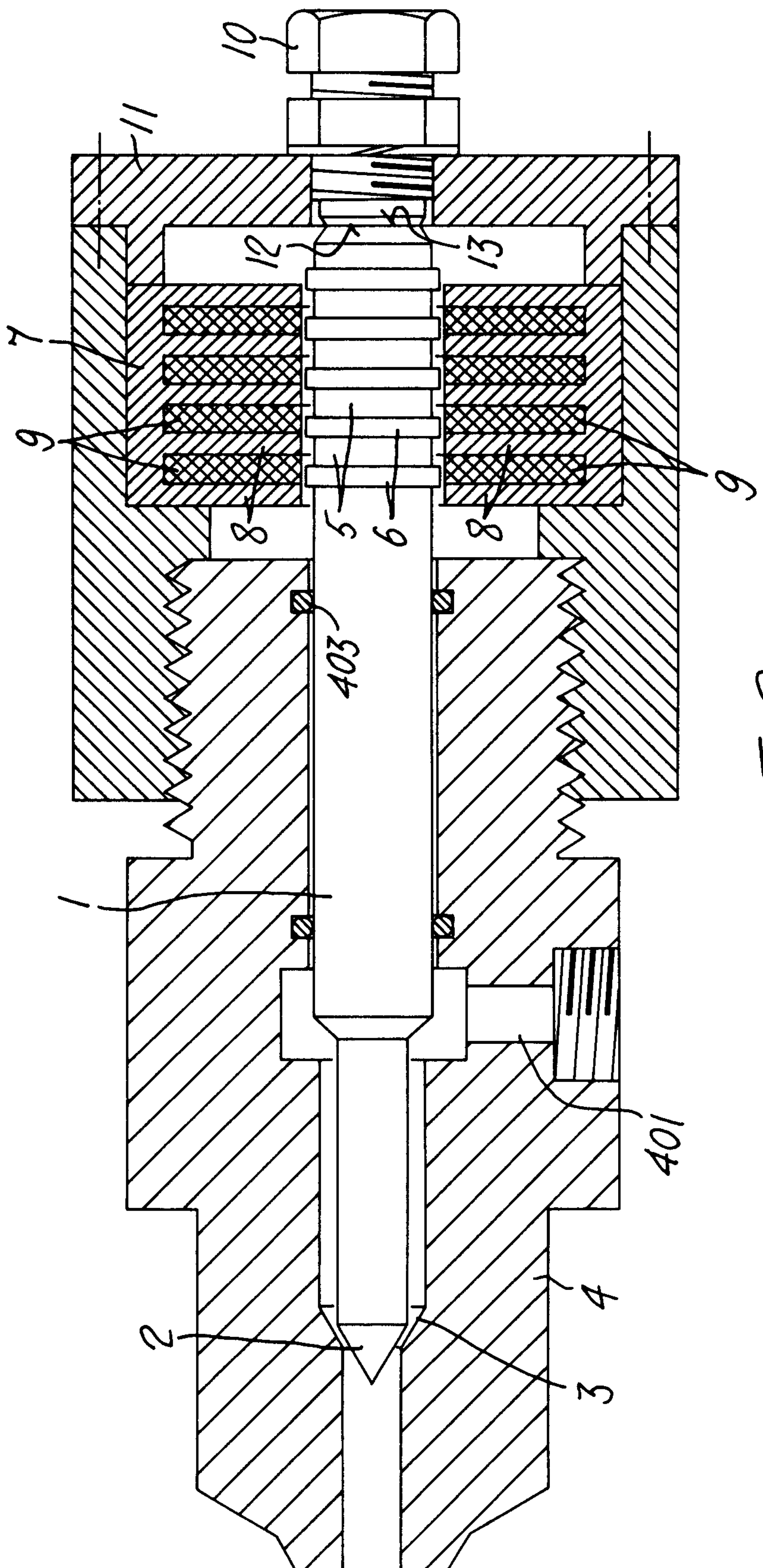

Fig.2

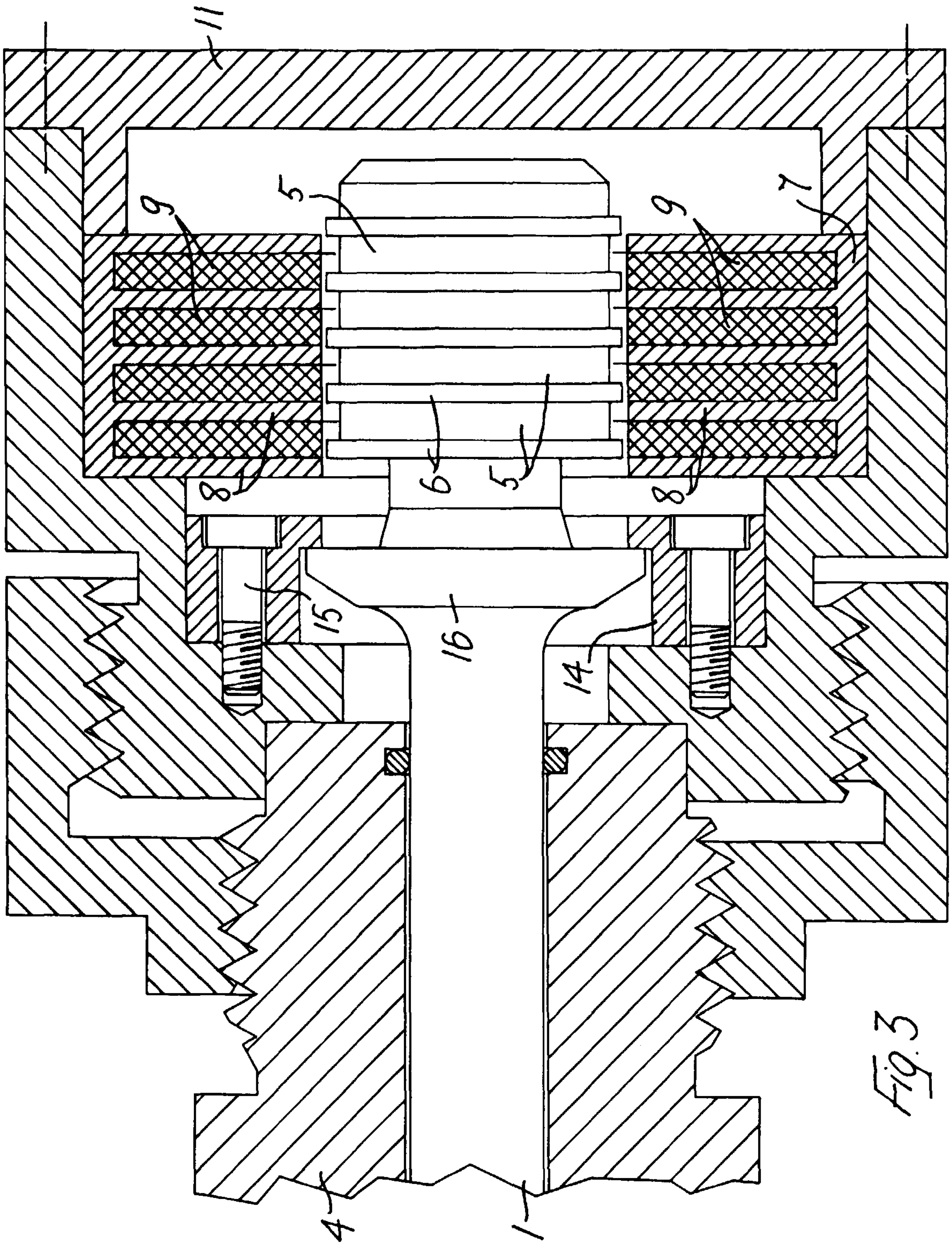

Fig. 3

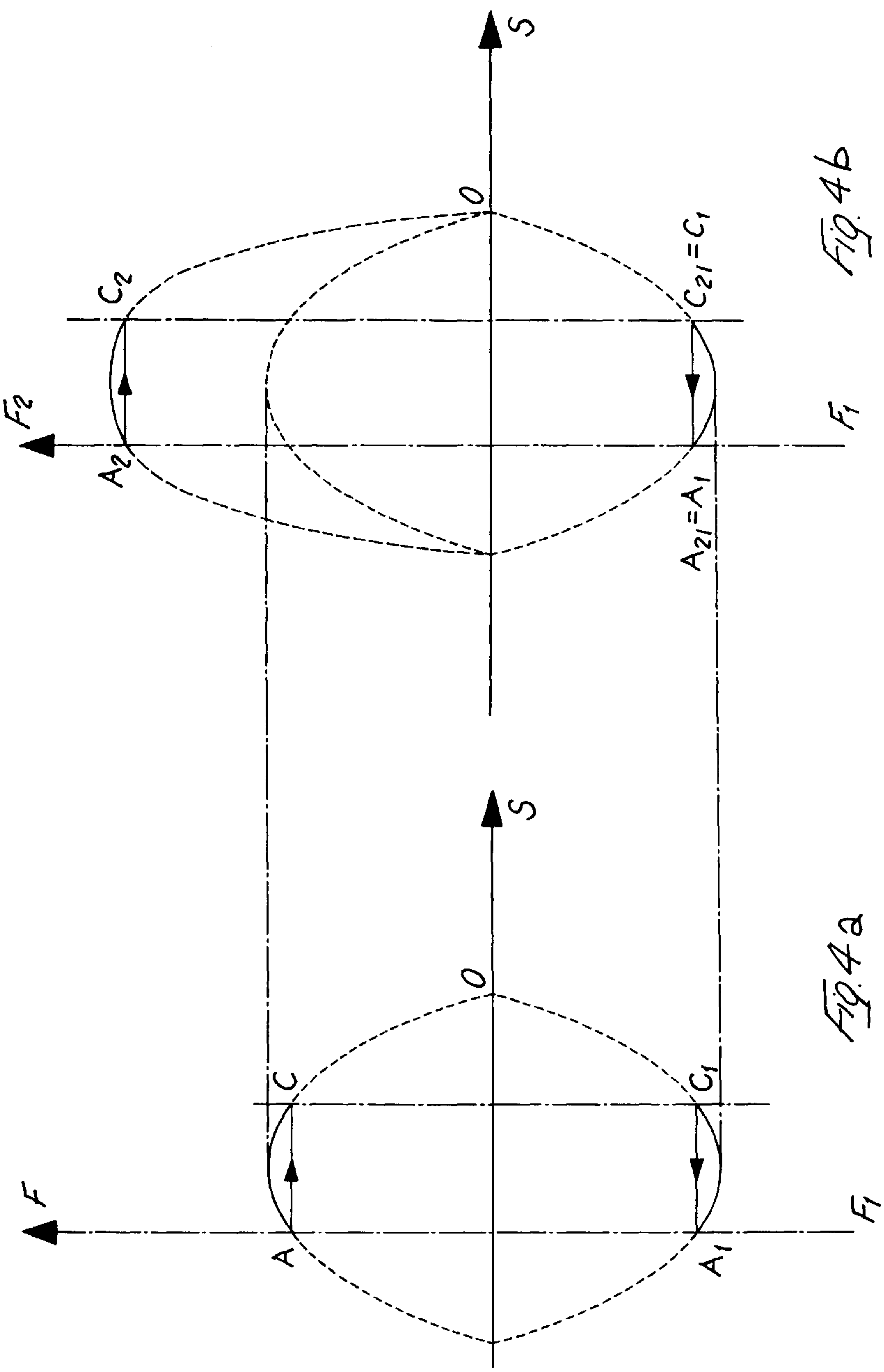

Fig. 4b

Fig. 4a