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ELECTROMAGNETIC APPARATUS FOR PRODUCING LINEAR MOTION

The present invention relates to electromagnetic apparatus for producing linear motion. A number of designs of linear electromagnetic actuator, sometimes termed a linear motor, have been produced. Various linear motor configurations are described in W093/01646. The devices to which this prior art relates have axial symmetry and are formed as piston-in-cylinder machines. The principal advantage of axial symmetry lies in the fact that the strong attractive forces between the magnetic elements of the stator and the magnetic elements of the armature are balanced about a central axis, so that the bearings of the machine do not need to withstand attractive forces.

A further advantage of the axially-symmetric construction is that the magnetic fields of the machine, whether generated as a result of electrical currents in conductors or produced by permanent magnets, can be contained within an outer steel case of the actuator. However they are generated, the magnetic fields can intersect the electrical coils of the machine with a high degree of efficiency.

Yet another advantage of the axially-symmetric construction is that, by utilising a cylindrical stator it is possible to form a sliding seal between the stator

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and the armature, which then allows of the possibility of creating a gas spring between the stator and armature by closing one end of the stator. Such an arrangement is described in more detail in the Applicant's international application PCT/GB98/02823.

All these known linear actuators are constructed and designed to apply a force between machine components connected or mechanically linked to the stator and armature, for which purpose these have a configuration which permits such connection. However, there are certain mechanical systems in which it is not required to connect a moving element physically to a drive element. In such circumstances the armature of the actuator does not have to have a continuous direct connection to the external environment. For example, it may be required for an element to be repeatedly driven to reciprocate along a guide member so as to deliver energy at the ends of its stroke when it changes direction. A road breaker or so-called "pneumatic hammer" works in this way by the alternate application of opposite forces by directing pressure fluid alternately into opposite chambers of a pneumatic cylinder with a flutter valve.

If the moving element has significant inertia, against which the external "stator" of the machine is designed to experience a reaction, a controlled vibration can be applied: this may be used for example in association with

earth-moving machinery. As a third example, the motion of the an unrestricted piston might be used to vary the total enclosed volume and/or pressure of a fluid system to which the piston chamber is connected. Such a machine might be used as a fluid pump, to dispense metered fluid, to vary the pressure in a sensory pad or to form part of a sensitive and precise fluid pressure suspension system.

Examples of such devices are disclosed in patent specifications US4965864, GB 6 452 81 and GB 2 017 420.

Specification US4965864 discloses a pump in which there is a hollow cylindrical stator surrounded by a sequence of coils and an armature which acts as the pump piston. The armature is a series of magnets arranged to produce a succession of radially oriented magnetic fields of the same sense. The coils are energised sequentially to cause the armature to oscillate within the stator and perform the pumping action.

Specification GB 6 452 81 discloses a solenoid device which works on the variable reluctance principle. The device consists of a plurality of sequential coils surrounding a hollow cylindrical chamber. A magnetic armature has an axial length such that it overlaps two adjacent coils. Successive energising of the two adjacent coils overlapped by the armature causes a linear motion of the armature, either in a single direction or

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Specification GB 2 017 420 again discloses a electromagnetic pump which has an armature which acts as an piston and which is caused to reciprocate within a stator chamber by electromagnetic interaction between the armature and a winding surrounding the stator and which produces a reciprocating magnetic field which causes corresponding movement in the armature.

In this case the armature is made of an electrically conducting but non-magnetic material such as aluminum and the device acts, inefficiently, as a reciprocating linear induction motor.

The present invention seeks to provide a linear actuator comprising a stator and an armature in which the armature is not attached to an output member which protrudes from the stator, such as the actuator arm or piston rod of known such actuators. That is to say, the armature of this invention is a piston that is free (or substantially free) to move within the stator volume. As used in this specification the term "free piston" will be understood to mean a member movable within a working volume without having a force-transmitting member such as a piston rod.

According to the present invention, therefore, the present invention provides electromagnetic apparatus for producing an axially directed force, comprising a stator with closed ends defining a working volume, a plurality of axially-spaced electrical coils surrounding the stator, an armature in the form of a free piston as hereinbefore defined axially movable within the said working volume, and means for applying electric currents to the coils so as to cause the armature to oscillate within the working volume in the stator, characterised in that the stator electrical coils are so connected as to form a multi-phase winding, the armature includes means for producing a radially-directed magnetic field the

polarity of which alternates along the axis of the armature, the radially directed magnetic field of the armature being arranged to intersect the coils of the stator in accordance with the pattern of the multi-phase winding constituted by the said coils such that an axially-directed electromagnetic force is generated when currents of appropriate phase and magnitude are caused to flow in the coils of the stator.

Preferably the physical parameters of the device are so chosen that the electrical coils may be connected to an electronic drive unit for controlling the phase, frequency or amplitude of the current in the coils so as to cause the desired axially-directed electromagnetic force to be created between the armature and the stator.

In one embodiment the armature and the stator are of circular cross section. This makes it easy for the outer surface of the armature to be sealed with respect to the internal surface of the stator, so as to prevent or at least restrict fluid flow between the volumes on either side of the piston.

Means may be provided for sensing the position of the piston so as to optimise the configuration of the currents supplied to the coils by the electronic drive unit.

The electronic drive unit may also be arranged to produce a signal representative of the current supplied to the actuator, the integral of such signal being used to control the pressure of a gas supply to at least to one side of a sealed armature.

Various embodiments of the present invention will now be more particularly described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic axial sectional view of a free piston actuator formed as a first embodiment of the present invention;

Figure 2 is an axial sectional view of an alternative embodiment having induction drive and a working tool;

Figure 3 is a schematic axial sectional view of an alternative embodiment utilised in a pressure pad drive system; and

Figure 4 is an axial sectional view of a further alternative embodiment employing ring magnets.

Figure 1 shows a particular form of the device in which the armature(piston) is required to be sealed to the inner surface of the armature tube. In this example the stator 1 carries an assembly of coils 2 extending circumferentially around the axis of the cylinder. The piston 3, moving on bearings 9 and seals 6, carries an arrangement of magnets 4 and polepieces 5 to produce a magnetic field alternating in polarity along the axis of the cylinder. The ends of the device include closures 7, in which, in this embodiment, there are provided fluid passages 8 so as to allow fluid to be moved by the action of the piston 3, if that motion is significant in relation to the enclosed volume.

Figure 2 shows an example of a free-piston actuator used to deliver repeated blows to a tool 10. The armature of this device consists of a hardened core 11 which may also contain lead to increase its mass. The core is keyed to an outer magnetic steel cylinder 12 which carries a series of slots in which are copper rings 13.

The coil assembly 2 is energised to produce an alternating magnetic field that travels along the axis of the piston. This induces currents in the armature rings 13 so as to produce a second alternating magnetic field, whose interaction with the first field accelerates the piston. It is necessary for the piston to be fitted with simple bearing rings (not shown, but similar to those of 9 in Figure 1). Nevertheless, it should be noted that the inductive forces that accelerate the piston also act to hold it away from the sides of the cylinder when in motion; such bearings do not therefore need to be of high quality.

Arrangements (not shown) are made to allow air or other gas within the cylinder 12 to pass freely between the opposing ends of the device shown in Figure 2, so as not to impede the motion of the piston.

It will be understood that the electromagnetic configuration of the invention is not restricted to the use of permanent magnets and an ironless stator assembly,

as shown by way of example in Figure 1, or to the use of an induction technique as shown by way of example in Figure 2. The armature or piston may, with advantage in certain conditions, use a variable-reluctance drive technique and/or the stator may have slots housing the coils.

Figure 3 shows a particular form of the actuator in relation to a pressure pad 15 carrying a load 19. The principal parts of the actuator device are similar to those described in Figure 1.

In this example the piston is shown as being provided with bearings 9 but to be sealed to the pressure pad 15 and to the source of pressurising fluid by bellows 18.

Figure 4 shows a modified form of the device illustrated in Figure 3, in that the axially-alternate magnetic field of the piston is produced by plane rings of magnetic material instead of discs. This technique allows the device to be of lightweight construction whilst applying force to a diaphragm 20 having an area larger than that of the magnets.

As described in the Applicant's International Patent Application PCT/GB98/02823 the time integral of the current consumed by the device is continuously computed and the fluid pressure in the volume 17 beneath the

piston is frequently adjusted to bring this integral to zero. This control technique ensures that the mean values of the pressures above and below the piston are equalised.

Position-sensing means (not shown) are also utilised by the control system to ensure that the median position of the piston is in the central region of the actuator.

It will be understood that the use of a bellows to replace the piston seal removes the constraint that the piston and the internal surface of the armature should be of circular cross-section.

It will be further understood that the principles of this invention are not compromised by the use of springs or equivalent compliances to provide a mechanical bias to the position of the piston in the absence of electrical power and that such compliant biasing devices may utilise permanent magnetic fields. In embodiments in which the armature is intended, in use, to reciprocate at high frequency the air trapped in the stator cylinder on either side of the pistons may act as a gas spring to cushion the impact at each end of its stroke. The piston/cylinder seal does not have to be very airtight in that the periodic motion may have a sufficiently high frequency for leakage effect to be minimal.

CLAIMS

1. Electromagnetic apparatus for producing an axially directed force, comprising a stator (1) with closed ends (7) defining a working volume, a plurality of axially-spaced electrical coils (2) surrounding the stator (1), an armature (3) in the form of a free piston as hereinbefore defined axially movable within the said working volume, and means for applying electric currents to the coils so as to cause the armature to oscillate within the working volume in the stator, characterised in that the stator electrical coils are so connected as to form a multi-phase winding, the armature (3) includes means (4,5) for producing a radially-directed magnetic field the polarity of which alternates along the axis of the armature, the radially directed magnetic field of the armature being arranged to intersect the coils (2) of the stator in accordance with the pattern of the multi-phase winding constituted by the said coils such that an axially-directed electromagnetic force is generated when currents of appropriate phase and magnitude are caused to flow in the coils (2) of the stator (1).

2. Electromagnetic apparatus according to Claim 1, characterised in that there are provided means (17;18) for resisting resiliently the motion of the armature at or adjacent at least one end of the range of movement thereof within the stator.

3. Electromagnetic apparatus according to Claim 2, characterised in that the said resilient means comprises a closed volume (17) of compressible fluid between the armature and the said one end of the stator.

4. Electromagnetic apparatus according to any preceding claim characterised in that the armature is provided with at least one unitary annular conductive member (12,13) in which a plurality of electric currents and associated magnetic fields are induced by the changes in the magnetic fields induced in the body of the armature (11) by currents flowing in the stator coils (2), the said induced magnetic fields being such as to intersect the stator coil currents whereby to generate a resultant axial force.

5. Electromagnetic apparatus according to Claim 4 characterised in that the armature comprises a plurality

of unitary annular conductors (13) attached to a common ferro-magnetic body (12).

6. Electromagnetic apparatus according to any preceding claim characterised in that the reciprocating axial motion of the armature (11) includes impacts against an end stop (10) positioned at at least one end of the range of travel of the armature (11) within the working volume of the stator (1), so as to deliver to an external object the kinetic energy of the armature (11) resulting from its motion.

7. Electromagnetic apparatus according to Claim 6 characterised in that the end stop (10) is constituted by a working tool associated with the stator (1) and movable over at least a limited range of movement with respect thereto.

8. Electromagnetic apparatus according to any preceding claim characterised in that the armature (3;11) is provided with openings to allow the transfer of fluid from one side thereof to the other upon displacement of the armature within the working volume of the stator (1).

9. Electromagnetic apparatus according to any preceding claim wherein there are provided means for sensing the axial position of the armature within the stator, and the means for applying electric current to the stator coil so as to cause the armature to oscillate within the stator is adapted to respond to signals from the armature position sensor to ensure that the median position of the armature within the stator lies in the central region of the stator.

10. Electromagnetic apparatus according to any of Claims 1 to 5 or 8 to 9, characterised in that the working volume (17) within the stator is enclosed by a membrane (18) or bellows and a closed volume (16) within the stator communicates with a working volume (15) of variable dimensions outside the stator such that displacement of the armature (20) within the working volume of the stator creates pressure variations within a fluid transferred from the stator to the said volume of variable dimensions.

11. Electromagnetic apparatus as claimed in Claim 10 characterised in that the volume (15) of variable dimensions is in physical contact with a pressure pad

(19) for varying the pressure exerted over at least a limited part of the area thereof.

12. Electromagnetic apparatus according to any preceding claim characterised in that the armature includes means for producing a radially diverted magnetic field the polarity of which alternates along the axis of the armature, which latter is constrained to move between respective opposite end positions within the stator such that energy from the motion of the armature is transmitted solely through the stator or via a member carried thereby which is not physically connected to the armature.

13. Electromagnetic apparatus according to any preceding Claim, characterised in that the stator (1) has openings (8) to allow the ingress and egress of fluid from the working volume of the stator (1) upon displacement of the armature (3) within it.

14. Electromagnetic apparatus according to any preceding claim, characterised in that the armature (3) comprises or includes a plurality of permanent magnets (4) for producing the said alternating magnetic field.

15. Electromagnetic apparatus according to Claim 14, characterised in that the permanent magnets (4) are orientated with their direction of magnetisation parallel to the axis of the stator (1), and are provided with pole pieces (5) at each end for directing the magnetic fields produced by the magnets (4) radially from circumferential faces of the pole (5) pieces whereby to intersect the coils (2).

16. Electromagnetic apparatus according to Claim 15, characterised in that there are a plurality of permanent magnets (4) each with associated pole pieces (5) orientated such that the direction of magnetisation of adjacent magnets (4) is in opposite directions.

17. Electromagnetic apparatus according to any preceding claim, characterised in that the control means is operable to deliver a cyclic control function whereby to cause the armature (3) to reciprocate within the working volume of the stator (1).

18. Electromagnetic apparatus according to any preceding claim, characterised in that the stator has a wear-resistant lining over its internal surface and the

armature carries bearings (9) and/or seals (6) engaging the said lining whereby to guide the aramture (3) along its axial displacement within the working volume in the stator (1) and the seals (6) separate two opposite chambers within the stator (1) from communicating with one another.

19. Apparatus according to Claim 17 characterised in that the electromagnetic forces on the piston (3) and the controlled displacement thereof are arranged to modify in a predetermined manner the pressure of a fluid in at least one of the chambers separated by the piston (3).