Title: LINEAR STEPPER MOTOR, MAGNETIZING FIXTURE, AND METHODS

Abstract: In one preferred embodiment, a linear stepper motor (20), including; a stator structure (32); an axially extending, cylindrical, permanent magnet shaft (30) magnetically interacting with the stator structure (32); and the axially extending, cylindrical, permanent magnet shaft (30) having a smooth surface along a portion thereof with axially alternating radial N and S poles (34, 36) defined in the smooth surface. The present invention also provides a method of magnetizing the shaft of such a motor and a fixture (100) and method of manufacturing the fixture therefor. In another preferred embodiment of the invention, there is provided a shaft (200) for a linear stepper motor that can permit rotational motion. In yet another preferred embodiment of the invention, an "inside-out" motor (300) is provided in which the linearly moving member (314) is external to the stator structure (312).
For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.
Description

Linear Stepper Motor, Magnetizing Fixture, and Methods

Technical Field
The present invention relates to stepper motors generally and, more particularly, but not by way of limitation, to a novel linear stepper motor, a fixture for the magnetization of the shaft thereof, and methods of use and manufacture.

Background Art
Some linear stepper motors convert rotary motion to linear motion by mechanical means such as through the use of a threaded nut and lead screw. Conventional linear motors that directly transfer electromagnetic energy in the stator poles to linear movement of a shaft typically employ toothed structures or have relatively complicated slide/stator arrangements. In either case, the manufacture of such motors is relatively expensive and the motors typically have high parts counts.

A problem resides in producing a linear motor with a smooth shaft with alternating N and S poles. One technique is to glue together cylindrical segments of N and S magnets. That technique, however, is time consuming and results in a somewhat weak structure. Another technique is to roll a cylinder of ferromagnetic material over a flat plate orthogonal to a series of alternating N and S magnetic strips. This technique is somewhat clumsy and suffers from the fact that the resulting magnetized shaft is of fairly weak magnetic strength.

Some conventional motors are described in the following patent documents:

United States Patent No. 3,867,676, issued February 18, 1975, to Chai et al., and titled VARIABLE RELUCTANCE LINEAR STEPPER MOTOR,
describes such a motor that has toothed structures on the coils and on the linear member. The novelty of the patent appears to reside in the arrangement of the coils and the manner in which they are energized.

United States Patent No. 4,198,582, issued April 15, 1980, to Matthias et al., and titled HIGH PERFORMANCE STEPPER MOTOR, describes, in part, a variable reluctance linear stepper motor in which both the stator and the slider have nonmagnetic materials arranged therein such that flux leakage is reduced.

United States Patent No. 4,286,180, issued August 25, 1981, to Langley, and titled VARIABLE RELUCTANCE STEPPER MOTOR, describes, in part, such a motor having helically toothed stator and slide structures, the respective widths of the teeth having a predetermined relationship.

United States Patent No. 4,408,138, issued October 4, 1983, to Okamoto, and titled LINEAR STEPPER MOTOR, describes a linear stepper motor having toothed structures on the stator and on the slider. Coil-wound salient poles are provided on the slider. The novelty of the patent appears to reside in the arrangement of rollers and rails disposed between the stator and the slider.

United States Patent No. 4,607,197, issued August 19, 1986, to Conrad, and titled LINEAR AND ROTARY ACTUATOR, describes a variable reluctance linear/rotary motor in which the armature has axial rows of teeth radially spaced around the surface thereof. Selective energization of stator windings provides linear, rotary, or both linear and rotary motion of the armature.

United States Patent No. 4,622,609, issued November 11, 1986, to Barton, and titled READ/WRITE HEAD POSITIONING APPARATUS, describes a variable reluctance positioning device having toothed structures on facing surfaces of the stator and the armature and with coils placed on the armature.

United States Patent No. 4,695,777, issued September 22, 1987, to Asano, and titled VR TYPE LINEAR STEPPER MOTOR, describes such a
motor having toothed structures on the stator and on the slider, the toothed structures on the stator being on coil-wound salient poles. The toothed structures bear a predetermined relationship therebetween.

United States Patent No. 4,712,027, issued December 8, 1987, to Karidis, and titled RADIAL POLE LINEAR RELUCTANCE MOTOR, describes such a motor having a smooth double-helix stator shaft and a smooth laminated armature of alternate radial pole laminations and spacer laminations. This arrangement permits a balanced flux path and uses the stator and armature surfaces as slider bearing surfaces.

United States Patent No. 4,810,914, issued March 7, 1989, to Karidis et al., and titled LINEAR ACTUATOR WITH MULTIPLE CLOSED LOOP FLUX PATHS ESSENTIALLY ORTHOGONAL TO ITS AXIS, describes a variable reluctance actuator similar in pertinent respects to that described in the '027 patent above.

United States Patent No. 6,016,021, issued January 18, 2000, to Hinds, and titled LINEAR STEPPER MOTOR, describes a variable reluctance stepper motor similar in pertinent respects to the motor described in the '609 patent above. The novelty of the patent appears to reside in the method of forming the teeth.

Accordingly, it is a principal object of the present invention to provide a permanent magnet shaft for a linear stepper motor that has a smooth magnetized surface.

It is a further object of the invention to provide a linear stepper motor that has low parts counts and is simple and economical to manufacture.

It is an additional object of the invention to provide a method of magnetizing a smooth shaft for a linear stepper motor that is quick and economical.

It is another object of the invention to provide a fixture for magnetizing a smooth shaft for a linear stepper motor.

It is yet a further object of the invention to provide a fixture for
magnetizing a smooth shaft for a linear stepper motor that can be economically manufactured.

It is yet another object of the invention to provide such a stepper motor conventional coils each easily wound around a bobbin.

It is yet another object of the invention to provide such a stepper motor having a shaft that can rotate at any position at any time, whether or not the motor is on or off or the shaft is moving linearly.

Other objects of the present invention, as well as particular features, elements, and advantages thereof, will be elucidated in, or be apparent from, the following description and the accompanying drawing figures.

Disclosure of Invention

The present invention achieves the above objects, among others, by providing, in one preferred embodiment, a linear stepper motor, comprising; a stator structure; an axially extending, cylindrical, permanent magnet shaft magnetically interacting with said stator structure; and said axially extending, cylindrical, permanent magnet shaft having a smooth surface along a portion thereof with axially alternating radial N and S poles defined in said smooth surface. The present invention also provides a method of magnetizing the shaft of such a motor and a fixture and method of manufacturing the fixture therefor. In another preferred embodiment of the invention, there is provided a shaft for a linear stepper motor that can permit rotational motion. In yet another preferred embodiment of the invention, an “inside-out” motor is provided in which the linearly moving member is external to the stator structure.

Brief Description of the Drawings

Understanding of the present invention and the various aspects thereof will be facilitated by reference to the accompanying drawing figures, provided for purposes of illustration only and not intended to define the scope of the invention, on which:
Figure 1 is a fragmentary, side elevational view, partially in cross-section, of a linear stepper motor constructed according to a first embodiment of the present invention.

Figure 2 is a rear elevational view of the motor of Figure 1.

Figure 3 is an isometric view of a grooved mandrel for use in fabricating a fixture for magnetizing the shaft of the motor of Figure 1.

Figure 4 is an isometric view of the mandrel of Figure 3 with a conductive wire inserted in the grooves of the mandrel.

Figure 5 is an fragmentary, schematic, isometric view of the conductive wire showing the path of a direct current flowing therein.

Figure 6 is an isometric view, partially cut-away, showing the mandrel of Figure 3 inserted in a potting fixture.

Figure 7 is an isometric view showing a magnetizing fixture for magnetizing the shaft of the motor of Figure 1.

Figure 8 is an isometric view showing a shaft according to a second embodiment of the present invention.

Figure 9 is a top plan view of a linear motor constructed according to a third embodiment of the present invention.

Figure 10 is a cutaway side elevational view of the motor of Figure 9.

Figure 11 is a side elevational view of the moving member of the motor of Figure 9.

Figure 12 is a side elevational view of a mandrel for magnetizing the cylindrical moving member of the motor of Figure 9.

Figure 13 is an end elevational view of the mandrel of Figure 12.

Figure 14 is a fragmentary, schematic, isometric view of a conductive wire for use with the mandrel of Figure 12.

Figure 15 is an end elevational view of the conductive wire of Figure 14.

**Best Mode for Carrying Out the Invention**

Reference should now be made to the drawing figures on which similar or
identical elements are given consistent identifying numerals throughout the various figures thereof, and on which parenthetical references to figure numbers direct the reader to the view(s) on which the element(s) being described is (are) best seen, although the element(s) may be seen on other figures also.

Figure 1 illustrates a linear stepper motor, constructed according to a first embodiment of the present invention, and generally indicated by the reference numeral 20. Motor 20 includes a shaft, or slider, 30 having a smooth outer peripheral surface (at least the portion thereof illustrated) and inserted in a stator structure, generally indicated by the reference numeral 32, for axial back and forth motion of the shaft with respect to the stator structure.

Shaft 30 includes a plurality of alternating N and S nonsalient poles, as at 34 and 36, respectively, formed around the periphery thereof, which poles may be formed as described below. Shaft 30 is preferably a hollow cylinder of ceramic or rare earth magnetic material, although the shaft may be solid or may have a core of ferromagnetic or other material with a hollow cylinder of the magnetic material disposed around the core. Shaft 30 can be economically constructed, for example, by conventional extrusion techniques that can produce a shaft of any given length or the shaft can be cut to a suitable length from extruded stock. At least the portion of shaft 30 containing the N and S poles is non-segmented and is constructed of a single piece of material.

Stator structure 32 includes first and second, cylindrical, coils 40 and 42, respectively, encircling shaft 30, and conventionally wound on first and second annular bobbins 44 and 46. Bobbins 44 and 46 are formed of an electrically insulating material such as Delrin®. First and second bobbins 44 and 46 are spaced apart by a first spacer 50 and the second bobbin may be spaced apart from an end plate 52 of motor 20 by a second spacer 54. First and second spacers 50 and 54 may also provide bearing surfaces for shaft 30, in which case the first and second spacers are preferably of a material having a high degree of lubricity such as Delrin®.

First bobbin 44 spaces apart annular pole plates 60 and 62, while second
bobbin 46 spaces apart annular pole plates 64 and 66. A steel band 68 surrounds
and is in good electrical contact with annular pole plates 60, 62, 64, and 66, thus
completing the circular electromagnetic circuit. Annular pole plates 60, 62, 64,
and 66 have nonsalient poles.

It will be understood that, by suitable energization of first and second coil-
wound bobbins in a conventional manner, shaft 30 may be made to
incrementally “step” to the left or right on figure 1. It will be further understood
that one or both ends of shaft 30 may be attached to, or bear against, one or
more elements of another device (not shown).

While motor 20 is shown as having one set of two-phase stator sections,
that is, the motor has two coils, it will be understood that other arrangements are
possible as well. For example, two or more sets of two-phase stator sections
may be provided for greater power, the additional sets of stator sections being
added serially in a modular manner.

Figure 2 illustrates some of the elements of motor 20 (Figure 1) and
illustrates conductors 70 that are used to energize stator structure 32 and
mounting holes 72 defined in end plate 52.

Thus arranged, motor 20 as shown (Figure 1) in its minimum
configuration is constructed of only 11 individual elements that may be held
together principally with a suitable adhesive or other conventional means may
be provided to secure together the elements of motor 20.

Figure 3 illustrates a mandrel 100 that can be used in constructing a fixture
for use in magnetizing shaft 30 (Figure 1). Here a cylindrical mandrel 100 has a
plurality of parallel, cylindrical grooves, as at 110, cut in the outer periphery
thereof, the groove having a width approximating the diameter of a wire
conductor to be used in magnetizing shaft 30. Mandrel 100 is constructed of a
non-magnetic, non-electrically-conducting material, with the spacing of grooves
110 being determined by the final magnetic widths of poles 34 and 36 on shaft
30.

Figure 4 illustrates a conductive wire 150 serially disposed in grooves 110
in mandrel 100.

Figure 5 illustrates the current path in conductive wire 150, each nearly complete circle shown on Figure 5 representing a turn of conductive wire 150 in one of grooves 110. It will be noticed that the current flow represented by the arrows in conductive wire 150 in adjacent turns of the conductive wire are in opposite directions.

Figure 6 illustrates mandrel 100, with conductive wire 150 placed in grooves 110, disposed in a cylindrical, hollow potting fixture 200. In this step, a suitable potting compound, such as an epoxy material, is poured into an annulus 210 defined between the outer surface of mandrel 100 and the inner surface of potting fixture 200. After hardening, the potting compound holds conductive wire 150 in place in grooves 110.

Figure 7 illustrates a finished magnetizing fixture, generally indicated by the reference numeral 300. Fixture 300 comprises mandrel 100 with an outer coating of potting compound 310 and ends of conductive wire 150 extending therefrom. A central axial bore 320 has been created, or enlarged, through mandrel 100 to bring conductive wire 150 near to the inner surface of the mandrel or even to be partially exposed, as shown on Figure 7, if desired.

Shaft 30 of motor 20 (Figure 1) can now be inserted into fixture 300 and a high level of direct current passed through conductive wire 150 to magnetize alternating N and S poles 34 and 36 along a selected length thereof. Such an arrangement provides an economical and rapid method of magnetizing shaft 30 and nearly any strength of magnetization can be provided, depending on the magnet material, since only one quick burst of direct current is necessary and that can be in a wide range of voltages.

Motor 20 (Figure 1) has a number of important features. For example, motor 20 is of a brushless, magnetically coupled, bi-directional, non-arcing design, having long operational life, with permanently magnetized output shaft 30. Motor 20 runs on conventional stepper motor drives and can be microstepped for increased resolution and accuracy. Shaft 30 is the only
moving part and it can be rotated 360° continuously or intermittently in either
direction, at any time and at any linear position, including when motor 20 is not
energized. There is no conversion of rotary motion to linear motion with the
concomitant efficiency losses. There are no lead screws, ball screws, or ball
bearings to wear out and no lubrication is required. Motor 20 can operate in any
orientation and is back-driveable (especially at low or zero power input), that is,
shaft 30 can be moved by overcoming the magnetic force between the shaft and
annular pole plates 64 and 66. Performance of motor 20 can be increased with
shorter duty cycles and can be easily constructed for vacuum environments, that
is, it can be constructed of materials that do not out gas in a vacuum, the lack of
lubrication contributing to this feature. Shaft 30 when hollow allows the pass-
through of electrical, optical, and/or fluid lines, and/or the like.

Figure 8 illustrates a shaft for a linear stepper motor, according to a second
embodiment of the present invention, and generally indicated by the reference
numeral 200. Shaft 200 has impressed thereon a magnetic pattern to permit both
linear and rotary motion of the shaft. This pattern consists of alternating N and
S poles, as at 210 and 212, for linear stepping similar to N and S poles of shaft
30 (Figure 1). In addition, there is provided at least one pair of N and S
longitudinally extending poles 220 and 222 added to the section of shaft 200
where there are very weak or no radial poles due to the loop-back pattern of
electrical conductor 150 (Figure 5) in mandrel 100 (Figures 3 and 4). This
makes use of the "dead band" area of a shaft normally magnetized for linear-
only motion.

For a stator assembly (not shown) to complete the motor of which shaft
200 is a part, a typical can-stack style stator section can be added (in series
axially) to stator structure 32 (Figure 1) in a modular fashion. This permits
rotation of shaft 200 or gives additional force to lock shaft 200 in place while
linear motion is taking place. Of course, both linear and rotary motion of shaft
200 may be simultaneously realized.

Figure 9 illustrates a linear motor constructed according to a third
embodiment of the present invention, the motor being generally indicated by the reference numeral 300. Motor 300 has a metallic base member 310 on which is fixedly disposed an internal stator structure 312 and has a cylindrical, hollow shaft 314 disposed around the stator structure. A threaded shaft 320 extends from the upper end of hollow shaft 314 for engagement with other components (not shown). Of course, other means of engagement may be provided, as well, the exact means of engagement not forming part of the present invention. Motor 300 is similar to motor 20 (Figure 1), except that the relative positions of shaft 30 and stator structure 32 are reversed.

Figure 10 illustrates more clearly the construction of motor 300. It can be seen that hollow shaft 314 moves linearly on the outside of stator structure 312. Additional two-phase stator sections can be axially stacked to increase force. In addition to the elements described above with respect to motor 20 (Figure 1), motor 300 includes two sleeve bearings 330 and 332. Metallic base member 310 provides not only support, but also serves to remove heat from motor 300.

Figure 11 illustrates hollow shaft 314 and illustrates that it is axially magnetized with alternating N and S poles, as at 340 and 342.

Figures 12-15 illustrate the components for magnetizing hollow shaft 314, the components being similar to those for magnetizing shaft 30 (Figures 1 and 3-5). A solid-core copper wire 350 (Figures 14 and 15) is wound in a special pattern on a cylindrical nonconductive mandrel 352 (Figures 12 and 13) which has grooves, as at 354, machined on its circumference to provide proper spacing and parallelism. A larger groove 360 (Figures 12 and 13) is machined along the length of mandrel 352 and is deeper than grooves 354 to accommodate loop-back sections of wire conductor 350. Mandrel 352 is then coated with a non-conductive epoxy, or similar material, and then the outside diameter of the mandrel is final machined to allow hollow shaft (Figure 11) to slide over the mandrel. Arrows on Figure 12 indicate the direction of electrical current flow in conductor 350 which creates alternating N and S poles, as at 340 and 342 (Figure 11) in hollow shaft 314.
In the embodiments of the present invention described above, it will be recognized that individual elements and/or features thereof are not necessarily limited to a particular embodiment but, where applicable, are interchangeable and can be used in any selected embodiment even though such may not be specifically shown.

Terms such as “upper”, “lower”, “inner”, “outer”, “inwardly”, “outwardly”, “vertical”, “horizontal”, and the like, when used herein, refer to the positions of the respective elements shown on the accompanying drawing figures and the present invention is not necessarily limited to such positions.

It will thus be seen that the objects set forth above, among those elucidated in, or made apparent from, the preceding description, are efficiently attained and, since certain changes may be made in the above construction and method without departing from the scope of the invention, it is intended that all matter contained in the above description or shown on the accompanying drawing figures shall be interpreted as illustrative only and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.
Claims

1. A linear stepper motor, comprising;
   (a) a stator structure;
   (b) an axially extending, cylindrical, permanent magnet shaft magnetically interacting with said stator structure; and
   (c) said axially extending, cylindrical, permanent magnet shaft having a smooth surface along a portion thereof with axially alternating radial N and S poles defined in said smooth surface.

2. A linear stepper motor, as defined in Claim 1, wherein: said axially extending, cylindrical permanent magnet shaft extends coaxially through said stator structure.

3. A linear stepper motor, as defined in Claim 1, wherein: said axially extending, cylindrical permanent magnet shaft coaxially surrounds said stator structure.

4. A linear stepper motor, as defined in Claim 1, wherein: at least one pair of N and S longitudinally extending poles is impressed on at least said smooth surface where there are weak or no radial poles, to permit rotation of said axially extending, cylindrical, permanent magnet shaft.

5. A linear stepper motor, as defined in Claim 1, wherein: said portion of said axially extending, cylindrical, permanent magnet shaft is hollow.

6. A linear stepper motor, as defined in Claim 1, wherein: said portion of said axially extending, cylindrical, permanent magnet shaft has a solid core.
7. A linear stepper motor, as defined in Claim 6, wherein: said solid core is formed from a ferromagnetic material.

8. A linear stepper motor, as defined in Claim 6, wherein: said solid core is formed from a non-magnetic material.

9. A linear stepper motor, as defined in Claim 1, wherein: said stator structure includes annular disks of a high lubricity material spacing apart elements of said stator structure and serving as bearing surfaces for said axially extending shaft.

10. A linear stepper motor, as defined in Claim 1, wherein: at least said portion of said axially extending, cylindrical, permanent magnet shaft is constructed of a single piece of material.

11. A linear stepper motor, as defined in Claim 1, wherein: said axially extending, cylindrical, permanent magnet shaft can rotate 360° continuously or intermittently in any direction, regardless of whether or not said linear stepper motor is energized.

12. A linear stepper motor, as defined in Claim 4, wherein: said at least one pair of N and S longitudinally extending poles permits said axially extending, cylindrical, permanent magnet shaft to be locked against rotation while linear motion takes place.

13. A linear stepper motor, as defined in Claim 1, wherein: said axially extending, cylindrical, smooth, permanent magnet shaft is back-driveable.
14. A linear stepper motor, as defined in Claim 1, wherein: said linear stepper motor is constructed to operate in any orientation.

15. A linear stepper motor, as defined in Claim 1, wherein: said stator structure has modular stator stacks.

16. A linear stepper motor as defined in Claim 1, wherein: said stator structure has conventionally wound coils.

17. A linear stepper motor, as defined in Claim 1, wherein said linear stepper motor includes no bearings.

18. A linear stepper motor, as defined in Claim 1, wherein: said linear stepper motor includes no lead screw and no ball screw.

19. A linear stepper motor, as defined in Claim 1, wherein: said linear stepper motor requires no lubrication of any part thereof.

20. A linear stepper motor, as defined in Claim 1, wherein: said linear stepper motor requires no conversion of rotary motion to linear motion.
21. A fixture for magnetizing axially alternating N and S poles defined circumferentially in a portion of an axially extending, cylindrical, smooth shaft, said fixture comprising:

   (a) a hollow cylindrical mandrel formed from a non-magnetic, non-electrically-conducting material;

   (b) a conductive wire disposed in parallel, circumferential channels defined in an outer surface of said mandrel;

   (c) a potting compound surrounding said mandrel to secure said conductive wire in place; and

   (d) a central bore defined axially and centrally through said mandrel and exposing or nearly exposing said conductive wire; and

   (e) said central bore being sized to accept axially inserted therein said portion of said axially extending, cylindrical, smooth shaft.

22. A fixture, as defined in Claim 21, wherein said conductive wire is placed in said parallel, circumferential channels such that direction of flow in said conductive wire of a direct current in adjacent ones of said parallel, circumferential channels is in opposite directions.
23. A method of providing axially alternating N and S poles in a portion of an axially extending, cylindrical, smooth shaft for a linear stepper motor, comprising:

(a) providing a magnetizing fixture comprising: a hollow cylindrical mandrel formed from a non-magnetic material; a conductive wire disposed in parallel, circumferential channels defined in an outer surface of said mandrel; a potting compound surrounding said mandrel to secure said conductive wire in place; and a central bore defined axially and centrally through said mandrel and exposing or nearly exposing said conductive wire; and said central bore being sized to accept axially inserted therein said portion of said axially extending, cylindrical, smooth shaft;

(b) inserting said portion of said axially extending, cylindrical shaft in said central bore; and

(c) providing a direct current through said conductive wire said conductive wire is placed in said parallel, circumferential channels such that direction of flow in said conductive wire of a direct current in adjacent ones of said parallel, circumferential channels is in opposite directions.

24. A method, as defined in Claim 23, further comprising: providing said conductive wire placed in said parallel, circumferential channels such that direction of flow in said conductive wire of a direct current in adjacent ones of said parallel, circumferential channels is in opposite directions.
25. A method of manufacturing a magnetizing fixture for magnetizing axially alternating N and S poles defined circumferentially in a portion of an outer periphery of an axially extending, cylindrical, smooth shaft, said method comprising:

(a) providing a plurality of parallel, circumferential channels defined in an outer surface of a cylindrical mandrel formed from a non-magnetic material;

(b) placing a conductive wire in said parallel, circumferential channels;

(c) providing a potting compound surrounding said mandrel to secure said conductive wire in place;

(d) forming a central bore defined axially and centrally through said mandrel and exposing or nearly exposing said conductive wire; and

(e) said central bore being sized to accept axially inserted therein said portion of said axially extending, cylindrical, smooth shaft.

26. A method, as defined in Claim 25, further comprising: providing said conductive wire placed in said parallel, circumferential channels such that direction of flow in said conductive wire of a direct current in adjacent ones of said parallel, circumferential channels is in opposite directions.