

Linear Actuator

Field of the invention

- 5 The present invention relates to a linear actuator that utilizes a double sided coil design with moving magnets, without utilizing any magnet back iron. The linear actuator is integrated with simple guidance support bearings, such as using shaft and bushing type of guidance bearings. The present invention can be used as a simple two position actuator, or as a servo actuator with position feedback, such as with a linear encoder.

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Background and discussion of prior art

- In the last few decades, pneumatic actuators have been widely used in industrial automation. This is due to the low cost of compressed air, simple and reliable functioning of such actuators and the availability of a wide range of supporting components and products. US
15 patent 4,987,822 describes such a linear actuator. However, to use a pneumatic actuator, a compressed air flexible hose needs to be supplied to the actuator. For equipment that is portable and not installed in a factory, compressed air is not easily available. This limits the usage of pneumatic actuators to facilities where compressed air supply is available. Moreover,
20 in order to control the flow of air in the actuator, valve devices such as solenoid valves are often required. Additional sensors are also required to detect the positions of the actuating rod. All the additional components needed make a pneumatic actuator expensive and complicated. Even if these components can be combined together, considerable space is needed. Another disadvantage is the response time of a pneumatic actuator. Pressure needs to
25 be built up to drive a piston, so the response is sluggish. Yet another disadvantage of a pneumatic actuator is that the holding force is not controllable, as it depends solely on the air pressure and the cross sectional area of the piston.

- It is an object of this invention to provide a linear actuator that can operate without
30 compressed air, low in cost, compact in size, reliable and easily controlled. The invention uses a novel electromagnetic design, more specifically a voice coil motor design, with integrated support bearings. The actuator can be used for simple two position control, like a pneumatic actuator, or it can be used with feedback devices, as a servo actuator.

- 35 Voice coil motors are electromagnetic devices that provide linear mechanical motion on the coil in response to the interaction of electrical and magnetic circuits. Fig 1 (prior art) shows a conventional linear moving coil actuator that consists of a cylindrical inner core 11 and an outer shell 12 which surrounds the inner core to define an annular space between the two. An

annular magnet 13 is mounted on the inner wall of the outer shell 12 while another annular magnet 14 is mounted on the outer wall of the inner core 11. This combination provides a single closed magnetic circuit. A circular coil winding 15 is positioned between the air gaps. When current is passed in the coil winding, a linear force is produced by the interaction of the
5 current and the magnetic flux density across the air gap. A voice coil motor has an advantage of faster response than a pneumatic actuator, since it can be controlled by the currents and since the inductance of the coils is very low.

U.S. Patent No. 4,692,999 issued to Frandsen discloses a moving coil actuator that uses 2
10 annular magnets 14 attached on the inner wall of the outer shell 12 to provide a flux path towards a center cylindrical core. In this configuration, the moving coil assembly is formed by dual coil sections instead of a single coil. This dual coil design allows the coil winding to interact or "cut" the air gap at 2 positions. This results in a larger linear force, and an improvement in the efficiency of the moving coil actuator.

15 U.S. Patent No. 6,787,943 issued to Godkin discloses another moving coil actuator with rectangular coils and rectangular magnets. In this design, the coil assembly is positioned in the air gap between two magnet track assemblies, and moved between these two magnet track assemblies when current is applied to the coils. With a moving coil, this voice coil actuator
20 suffers from the two problems described above, mainly the cable movement and reliability, as well as the heat generation issue. If the magnet track assemblies are moved instead of the coil, the moving mass will be very much higher, and the performance of the actuator will be greatly reduced.

25 US Patent Application No. US 2010/0133924 A1 also discloses a linear motor actuator with a snap-together design. The moving coil is attached to a bobbin assembly that moves with a piston, which in turn is guided by a spline bearing. While not described in the patent application, this design requires a flexible cable that moves with the coil assembly, thereby limiting its reliability or life time.

30 However, there are a few limitations associated with both the conventional voice coil motor design and the cited documents referred herein. Firstly, the coil assembly is typically moved, since the magnetic core which comprises magnets and steel core is heavy. This requires the cables that are connected to the coil assembly to be moved as well. Typically high flexible
35 cables are used, such as those with fine strands of copper conductors insulated with silicone rubber. These cables are not suitable for very high frequency motion, or when the motion involves longer distance to be travelled. Hence, the reliability of such an actuator is limited. Another disadvantage of the voice coil actuator is the heat generated in the coils. Since the

coil assembly is the part that moves, the heat has no way to escape except through the load. This is undesirable, as it causes thermal expansion in the load, affecting the accuracy of motion. Moreover, the continuous current of the actuator is limited, since the heat cannot escape elsewhere.

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What is desirable is a linear actuator in which the magnets of the linear actuator move. Since the coils and the cables to the coils are fixed, and only the magnet and a structure on which the magnets are fixed are moved, the reliability of the linear actuator is much improved. The improved linear actuator also eliminates the need to use flexible cables

10 which are costly and are prone to regular replacement due to frequent movements.

Summary Of Invention

A first object of the invention is a linear actuator comprising

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one or more coils mounted to a first coil back iron;

one or more coils mounted to a second coil back iron;

20 two or more magnets positioned in the centre between the first coil back iron and the second coil back iron;

a first air gap between the first coil back iron and the magnets;

25 a second air gap between the second coil back iron and the magnets;

the first air gap and the second air gap being the same width; and

30 a structure that holds the magnets in place, the structure having a first bushing mounted on a first fixed shaft and a second bushing mounted on a second fixed shaft;

35 so that the structure glides along the first fixed shaft and the second fixed shaft from a first position to a second position and back when a current passes through the one or more coils.

Preferably, the structure glide on linear bearings instead of bushings and shafts.

Alternatively, the structure glide on a first runner block on a first rail and a second runner block on a second rail.

Preferably, both shafts move while keeping the bushings stationary.

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Alternatively, the first shaft and a bushing moves while the second shaft and other bushing remains stationary.

Alternatively, the rails move while keeping the runner blocks of a linear bearing stationary.

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Preferably, limit sensors are added to detect the first position and second position of the actuator.

Preferably, a linear encoder or other feedback device is added to provide position feedback for servo control.

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Alternatively, a multi-phase coil is used instead of a single phase coil.

Alternatively, the structure is kept stationary while the two coil back iron and coils are moved.

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A subsidiary object of the invention is for the linear actuator to include an amplifier with logic control and power electronics, where the direction of motion, the peak current, the peak current duration and the holding current of the linear actuator can be controlled.

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Preferably, the peak current, the peak current duration and the holding current of the amplifier can be adjusted and preset.

A subsidiary object of the invention is a structure made from non magnetic material.

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Preferably, the structure is made from non magnetic material such as aluminum.

Alternatively, the structure is made from non magnetic material such as fiber reinforced resin.

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Alternatively, the structure is made from non magnetic material or other materials which are of low mass density.

Brief Description Of The Drawings

For a better understanding of the invention, its advantages, and the objects attained by its use, reference should now be made to the accompanying drawings. The accompanying
5 drawings illustrate one or more embodiments of the invention and together with the description herein, serve to explain the workings and principles of the invention.

Fig. 1 (prior art) shows a conventional linear moving coil actuator.

10 Fig. 2 shows a front view of the linear actuator of this invention.

Fig 3 shows a side view of the linear actuator of this invention.

Fig 4 is an isometric view of a structure which illustrates how the magnets are fixed to the
15 empty pockets of the structure.

Fig 5 shows the use of linear guidance bearings in the linear actuator of this invention.

Fig 6 is a three dimensional rear view of the linear actuator of this invention, with the
20 direction of motion indicated

Fig 7 shows a schematic of the design of an amplifier used in the linear actuator of this invention.

25 Fig 8 is a schematic for an electrical circuit for the control connections of the amplifier.

Fig 9 is a schematic for an electrical circuit for power connections for the amplifier.

Fig 10 shows the result from an actual test of the amplifier with a linear actuator according
30 to the invention.

Detailed Description Of The Preferred Embodiment

The present invention uses a different approach from conventional voice coil designs, where a
35 row of magnets are positioned between two coil assemblies. The linear actuator of this invention would be described with reference to Fig. 2 onwards.

Fig 2 shows a front view of the linear actuator. There are two coils 21a, 21b mounted to coil back iron 22a, 22b respectively. Rare earth magnets 23a, 23b (not shown) are positioned in the centre, between the two coils 21a, 21b. The air gap between the coil back iron 22a and magnet 23a is the same as the air gap between the coil back iron 22b and magnet 23b (not shown). The magnets 23a, 23b are mounted on a structure 24, which has two bushings 25a, 25b mounted on it. The structure 24 can be made from any non magnetic material that has low density and good mechanical properties, such as aluminum or fiber reinforced resin material. This reduces the moving mass significantly, thereby improving the dynamics of the actuator, thereby achieving higher accelerations and motion performance. The bushings 25a, 25b enable the structure 24 to glide along two fixed shafts 26a, 26b, which is in the direction of motion. The coil back iron 22a, 22b are just simple metal plates, although the material needs to be permeable to magnetic flux, such as stainless steel 430 or low carbon steel. These plates are flat, without any teeth or laminations and do not require special machining process. It is held by casings 27a, 27b which may be made from aluminum, plastic or other materials.

Fig 3 shows a side view of the linear actuator, with the direction of motion indicated. Unlike conventional voice coil designs, the magnets 23a, 23b are moved instead of the coils 21a, 21b. This means that the cables that are connected to the coils 21a, 21b which supply the currents are fixed as well. The cables can therefore be of an ordinary type, and not the high flexible type of cables which are much more costly. The polarities of the two magnets 23a, 23b are configured such that the magnetic flux circuit 33 is closed by the coil back iron 22a, 22b. Unlike conventional designs, there is no magnet back iron, as the magnets are mounted onto a non magnetic structure 24. Hence, when a current is passed through coils 21a, 21b, a resultant force is produced which forces the structure 24 to move towards the right or the left, depending on the direction of the current. It may be observed that the attraction force F_1 between the coil back iron 22a and the magnets 23a is completely compensated or balanced by the attraction force F_2 between the coil back iron 22b and the magnets 23b. There is therefore no net attraction force acting on the magnets 23a, 23b or the structure 24 which holds the magnets 23a, 23b. Consequently, the bearings used to support the structure 24 need not be very large, and just required to allow for guiding motion alone.

Fig 4 is an isometric view of a structure 24, which illustrates how the magnets 23a, 23b are fixed to the empty pockets in the structure 24. The magnets 23a, 23b may be fixed to the structure 24 by strong epoxy. The entire structure assembly, including the bushings 25a, 25b glide along the shafts 26a, 26b, while the both ends of the shafts 26a, 26b are fixed to the casings 27a, 27b of the actuator (not shown).

- Fig 5 shows the use of linear guidance bearings 52a, 52b in the linear actuator of this invention. While a bushing and shaft bearing system is shown in Fig 3 and Fig 4, it is also possible to use linear guidance bearings 52a, 52b, such as those shown in Fig 5. Other bearing support configurations are also possible, such as moving both shafts 26a, 26b while keeping the bushings 25a, 25b stationary, moving a shaft and a bushing while keeping the other shaft and other bushing stationary, or moving the rails while keeping the runner block of a linear bearing stationary. It is understood that such variations fall within the spirit and scope of the invention.
- Fig 6 is a three dimensional rear view of the linear actuator of this invention, with the direction of motion indicated. The load is to be mounted at the front side 61a of the structure 24. The rear side 61b of the structure 24 is designed to protrude out from the actuator main body 62. While stoppers are designed in the actuator to mechanically stop the motion of the structure 24, it is necessary for sensors 64 to confirm that these end positions have been reached. Hence, rubber magnets 63 are mounted onto the rear side 61b of the structure 24, with a magnetic sensor 64 to detect the magnetic flux when the magnets 63 move across the sensors 64. In this way, the limit positions may be detected. The linear actuators of this invention are therefore very economical and compact. Alternatively, reflective sensors or other types of sensors may be used for limits detection.
- In order to provide a simple two position actuation solution, an amplifier is designed for the linear actuator of this invention. Fig 7 shows a schematic of the design of the amplifier. The amplifier comprises two parts: the amplifier logic control and the amplifier power electronics.
- Table A shows the control connections of the amplifier.

Pin	Function	Remarks
EI	Amplifier Enable Input	Sets active high to turn on amplifier
ER	Amplifier Enable Input Return	
DI	Motor Direction Input	Controls the forward or reverse direction
DR	Motor Direction Input Return	

Table B shows the power connections for the amplifier.

Pin	Function	Remarks
VP	Positive Power Input	Can be 12 VDC or 24 VDC
Gnd	Power Return/Ground	
M1	Motor Power Output 1	
M2	Motor Power Output 2	

- Fig 8 shows the result from an actual test of the amplifier with a linear actuator according to the invention. The operation of the amplifier is described as follows. Upon initial power up, at time T1, with the EI input set to Active High, the linear actuator would move in whatever direction the DI input is set to. Assuming that the DI is Active Low, M1 would send a PWM waveform out. This causes a small ramp up to the preset holding current value, as shown in the Motor Currents graph. As the linear actuator moves to the end stopper, this preset holding current will cause the actuator to be exerting a constant force on the end stopper, since the force produced by a voice coil actuator is proportional to current applied. By changing the value of this preset holding current, it is therefore possible to control the holding force of this actuator.
- At time T2, DI is set to Active High. This activates DT, which is the peak current application time. This DT would switch the ramping current momentarily for a fixed period of time that is determined by the DT value. This particular feature is to allow an instantaneous peak current (which can be preset) to be applied to the voice coil actuator. After the duration set in DT, the current will drop to the holding current again. This feature enables the linear actuator to move quickly to the other position when it is activated, and yet it will protect the actuator against prolong periods of high currents, which will cause the coils to overheat and possibly be damaged. Whenever DI changes its state, this operation will be repeated, such as at T3 and so on.
- With this amplifier, it is possible to provide a low cost, easy to use solution for two position actuation with the linear actuator. While this linear actuator can be used for a two position control, it is also possible to use it as a servo actuator, where a feedback device is attached. Referring to Fig 6, a scale 65 may be attached to the rear side 61b of the structure. A linear encoder read head 66 can be fixed to the actuator body 62, so that encoder feedback can be used to provide closed loop control of the linear actuator.

While there are only two coils shown in the design of the linear actuator in Fig 3, it is possible to have multiple sets of coils as well, to increase the force of the linear actuator. For example,

Fig 9 shows an embodiment of the linear actuator, where there are 4 coils, 111a, 111b, 112a and 112b. The number of magnets is therefore also multiplied by two, with four magnets 113, 114, 115 and 116. There could be other variations more sets of coils and magnets.

- 5 While the linear actuator of this invention described so far uses a single phase coil, it is also possible to use multiple phases. In Fig 10, a three phase coil design is shown, where there are coils 121a and 122a corresponding to phase A, coils 121b and 122b corresponding to phase B, and coils 121c and 122c corresponding to phase C. In this case, the actuator is a brushless motor, rather than a voice coil motor.

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While the design of the linear actuator described involves moving the magnets and keeping the coils stationary, for applications that require the distance travelled to be very long, it is also possible to move the coils and coil back iron, while keeping the magnets stationary.

15 Advantageous Effects of the Invention

- With an amplifier designed to provide peak current, peak current duration and continuous holding current control, this linear actuator provides two position actuation with a much faster response than traditional pneumatic actuators. It also allows more flexibility for users to control the amount of holding force by presetting the holding current to the actuator.

- Unlike conventional moving coil actuators, the magnets 23a, 23b of the linear actuator of this invention are moved. Since the coils 21a, 21b and the cables to the coils 21a, 21b are fixed, and only the structure 24 and magnets 23a, 23b are moved, the reliability of the actuator is much improved. This also eliminates the need to use flexible cables which are costly.

- The inventive linear actuator involves attaching magnets to a structure 24 that can be made from aluminum or other light weight material, and does not involve any magnet back iron. This reduces the moving mass significantly. Hence, higher accelerations and dynamic performance can be achieved.

- Since the coils 21a, 21b are fixed to the coil back iron 22a, 22b, which in turn are assembled to the actuator main body, the heat generated from the coils 21a, 21b is transmitted to the actuator body, and not directly to the load. Essentially the coil back iron 22a, 22b and the actuator body becomes a very effective heat sink for the coils 21a, 21b, resulting in higher continuous current that can be used with the actuator. This results in better performance and higher force achieved with the linear actuator of this invention.

Since the linear actuator of this invention provides two sets of coil 21a, 21b mounted to two coil back iron 22a, 22b that are equally spaced from the magnets 23a, 23b in the centre, there is no net attraction force on the structure 24. This allows us to use simple, small
5 bearings to support the structure 24 in the linear actuator. This reduces the costs and the size of the actuator design.

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Claims:

1. A linear actuator comprising
 - 5 one or more coils 21a, 21b mounted to a first coil back iron 22a;

one or more coils 21a, 21b mounted to a second coil back iron 22b;

two or more magnets 23a, 23b positioned in the centre between the first coil back iron
10 22a and the second coil back iron 22b;

a first air gap between the first coil back iron 22a and the magnets 23a;

a second air gap between the second coil back iron 22b and the magnets 23b;
15 the first air gap and the second air gap being the same width; and

a structure 24 that holds the magnets 23a, 23b in place, the structure 24 having a first
bushing 25a mounted on a first fixed shaft 26a and a second bushing 25b mounted
20 on a second fixed shaft 26b;

wherein the structure 24 glides along the first fixed shaft 26a and the second fixed shaft
26b from a first position to a second position and back when a current passes through
the one or more coils 21a, 21b.
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 2. The linear actuator of claim 1, wherein the structure 24 glide on linear bearings 52a,
52b instead of bushings 25a, 25b and shafts 26a, 26b.
 3. The linear actuator of claim 1, wherein the structure 24 glide on a first runner block on a
30 first rail and a second runner block on a second rail.
 4. The linear actuator of claim 1, wherein both shafts 26a, 26b move while keeping the
bushings 25a, 25b stationary.
 - 35 5. The linear actuator of claim 1, wherein the first shaft 26a and a bushing 25a moves
while the second shaft 26b and other bushing 25b remains stationary.

6. The linear actuator of claim 1, wherein the rails are moved while keeping the runner blocks of a linear bearings 52a, 52b stationary.
7. The linear actuator of claim 1, wherein limit sensors are added to detect the first position and second position of the actuator.
8. The linear actuator of claim 1, wherein a linear encoder or other feedback device is added to provide position feedback for servo control.
9. The linear actuator of claim 1, wherein a multi-phase coil is used instead of a single phase coil.
10. The linear actuator of claim 1, wherein the structure 24 is kept stationary while the two coil back iron 22a, 22b and coils 21a, 21b are moved.
11. The linear actuator of Claim 1, having additionally an amplifier with logic control and power electronics, where the direction of motion, the peak current, the peak current duration and the holding current of the linear actuator can be controlled.
12. The amplifier of claim 11 wherein the peak current, the peak current duration and the holding current can be adjusted and preset.
13. The structure 24 as claimed in Claim 1, said structure 24 being made from non magnetic material.
14. The structure 24 as claimed in Claim 13, said structure 24 being made from non magnetic material such as aluminum.
15. The structure 24 as claimed in Claim 13, said structure 24 being made from non magnetic material such as fiber reinforced resin
16. The structure 24 as claimed in Claim 13, said structure 24 being made from non magnetic material or other materials which are of low mass density.