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PATENT APPLICATION

for

LINEAR RECIPROCATING ACTUATOR UTILIZING A BRUSHLESS DC MOTOR

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DESCRIPTION

TITLE OF INVENTION

Linear Reciprocating Actuator Utilizing A Brushless DC Motor

FIELD OF INVENTION

This invention concern about a device that provides linear reciprocating motion powered by a brushless DC motor.

BACKGROUND OF INVENTION

Conventional motorized linear actuators found in the market today are driven by either the stepper or the hybrid motor. The stepper version is used for light applications while the stronger hybrid is used for heavier applications but is much costlier. A major drawback of these two motors is linear speed limitation.

This linear actuator invention is powered by a conventional Brushless DC (BLDC) motor and is able to produce high force at high reciprocating speeds. An internal nut and a lead screw convert the rotational motion of the BLDC motor to linear motion. In addition to the typical circuit that drives the BLDC motor, a position sensor and microcontroller are used to switch the motor clockwise and counter-clockwise at the correct instance.

BRIEF DESCRIPTION OF PRIOR ART

The Brushless DC motor, also known as the BLDC motor is a rotating electric machine which can be found in many applications, from toy cars to photocopier machines. They are generally preferred compared to other DC motors because of their longer life, higher efficiency, low EMI (electromagnetic interference), lower temperature rise, excellent instantaneous speed variation and low audible noise.

The typical BLDC motor has a 3-phase stator coil that generates magnetic field that “pulls” the rotor which essentially is made of permanent magnets formed into the shape of a ring. When the stator is energized in the correct sequence, the rotor rotates and moves as quickly as the rotating electromagnetic field. Hall sensors are commonly employed as the “brushless” commutation (electronic commutation) of the motor. They are placed next to the rotating rotor magnets and provide the “position” information of the rotor to the motor drive circuitry. This motor driver controls the smooth rotational movement of the rotor by firing (energizing) the correct set of stator coils based on the rotor position.

These motors also have controller features such as tachometer output, motor enable and direction input. The tachometer output is represented by a square wave (also known as tach pulses) which provide information on motor speed and number of rotations. The wave is generated when the magnetic field of ring-shaped magnet (tach magnet) which is attached to the rotor, cuts the path of a conductor that is laid onto the drive PC board. The motor enable feature functions like a switch that “enables” (turns on) and “disables” (turns off) the motor. Direction input is another switch that controls the direction of rotation.

Linear actuators are used in applications such as medical equipment, pumps, x-y tables, automation of any kind, valve control and many more. There are literally hundreds of types of linear actuator products in the motion control industry. Each type provides specialty in various parameter such as speed, accuracy, price range, thrust load, direct load, size constraints, axes of motion, etc. Linear actuators can be broken down into different classes

but the one that relates to this invention is one that provides reciprocating motion used in application such as vacuum pumps, compressors, engines, etc.

Hall position sensors are usually used as an integral part of a closed loop feedback control system. They are used in a variety of fields such as industrial automation, automotive components, semiconductor manufacturing, robotics and the like. As mentioned above, they are also used for electronic commutation in the BLDC motor.

The microcontroller is essentially a "special purpose mini computer" that executes one specific program that is stored in its memory. They have input and output ports that receives and sent signals to the device that it is controlling, in this case the BLDC motor. They are often small and low cost and require very little power to run them.

SUMMARY OF THE INVENTION

This linear actuator invention produces high linear force at high speeds and is powered by a conventional Brushless DC (BLDC) motor. Instead of a regular rotating shaft found in the normal BLDC motor, this “modified” motor has a shaft that extends and retracts in a reciprocating motion. Devices to be driven are attached to the end of this shaft.

Current linear actuators found today have a slightly different configuration. There is a nut that rides along an external screw thread driven by a motor. To prevent the nut from rotating with the screw, it has to be guided to move along a slide member that has to be as long as the traverse length of the nut. This slide member takes up space and these linear actuators may not be applicable when used in confined spaces. For example in a vacuum pump, the access hole to the diaphragm is made as small as possible to minimize air leaks. The linear actuator invention described here resolves this problem by doing away with the slide member. The moving shaft is the only component present outside the actuator body. This shaft can be made very narrow to fit through the small hole opening of the pump to access to the diaphragm.

The main components that make up this invention are the BLDC motor, lead screw, hollow spindle, mounting plate and position feedback system.

The Brushless DC Motor

The BLDC motor used here is a conventional type that comprises a stator with a wound coil, an outside-spin rotor with permanent magnets bonded to it and electronics required to drive the motor. In a typical motor, there is a shaft coming out of the motor body. This shaft is attached to the rotor and revolves together with it. It provides power to whatever device that it is driving. In this linear actuator, the shaft does not revolve. Instead, this shaft moves linearly along the rotor axis as it extends and retracts from the motor body. It provides “pull” and “push” force to the device that it is attached to, for example, a diaphragm in a vacuum pump. This shaft forms part of the lead screw, which will be explained in detail in the next section. From here onwards, we will refer this item as the lead screw.

The Lead Screw

The lead screw forms part of the mechanism that converts the rotational movement of the rotor to linear motion. It is made up of two different portions. The threaded portion of the lead screw mates with the internal thread of the hollow spindle. The other portion of the lead screw is a shaft that has a cross-section that is shaped to prevent rotational movement. This part of the lead screw extends out of the motor through a non-rotating hole with a shape that matches with the lead screw cross-section. Devices that require the reciprocating action are attached to the end of this shaft.

The Hollow Spindle

The hollow shaft is a component that drives the lead screw in a straight line. It is attached to the axis of the rotor and rotates with it. Inside the hollow spindle is an internal thread, which is engaged to the external thread of the lead screw. As the rotor turns, the threads of the hollow spindle and the lead screw convert the rotational motion into linear movement of the lead screw.

The Mounting Plate

The mounting plate has two purposes. Firstly, it is used to mount the linear actuator onto the device that is driving, for example onto the housing of a pump. Secondly, it prevents the lead screw from rotating with the rotor. The mounting plate has a hole with a shape that matches the anti-rotating shaft. The anti-rotating shaft of the lead screw slides in and out of this hole to create the linear reciprocating motion.

The Position Feedback System

The position feedback assembly comprises a sensor magnet, a hall effect sensor, a tach magnet, a tach pattern and a microcontroller.

The sensor magnet with two magnetic poles stacked along the axis of the lead screw stroke, is attached to the end of the lead screw.

The hall sensor is placed in a position where the sensor magnet is able to toggle its state when the lead screw is at the end of the retracting stroke.

A tach magnet in the shape of a ring is attached to the rotor and placed just above a tach pattern imprinted on the printed circuit board that houses the motor electronics circuitry. When the rotor turns, the magnetic fields from tach magnet cut across the tach pattern which then produces a series of electrical pulses. When viewed on an oscilloscope, they have a square waveform. The frequency of this series of pulses is proportional to the speed of the rotor.

The microcontroller circuit basically consists of a programmable microcontroller chip and its supporting electronic devices and is typically integrated onto a printed circuit board (PCB) together with the motor drive electronics. The microcontroller circuit is connected to the position hall sensor and the motor drive circuitry. The microcontroller, which acts as the “brain” of this system senses the various signals and executes the necessary tasks based on the firmware or program codes that has been pre-programmed into it. One such task for example, is “commanding” the motor to start, stop and reverse its direction. Actuator stroke variation due to rotor inertia or changing loads can also be fixed by incorporating a correction algorithm into the firmware. Additional features such as those related to safety can also be included.

Actuator Operation

During operation the rotor rotates like a regular motor. The rotary motion of the rotor is transferred to the internal hollow spindle. The internal screw thread inside this hollow spindle converts the rotational motion into linear movement of the mating lead screw.

When the actuator is first switched on, the microcontroller commands the motor to rotate in a direction that causes the lead screw to retract. When the lead screw reaches the retracted end of the stroke, the hall sensor detects the change in the magnetic field of the sensor magnet

(placed at the end of the moving lead screw) as the magnet passes across it, and this signal is captured by the microcontroller. The microcontroller then commands the rotor to stop and reverse its direction of rotation causing the lead screw to move in the opposite direction (extend). During shaft extension, the microcontroller keeps track of the traverse length by counting the tach pulses generated by the interaction of the magnetic fields of the tach magnet and the tach pattern on the printed circuit board. When the tach count reaches a preset value, the microcontroller tells the rotor to change its direction again. The lead screw will now begin to retract and this cycle is repeated.

However due to inertia, the rotor does not stop instantaneously when changing direction. This may cause the reciprocating shaft to overshoot its intended stop position. Loads that vary in magnitude will also affect the stroke length of the actuator. In view of this potential problem, a special set of instruction codes or algorithm is added to the firmware to correct this phenomenon.

By changing the size of the BLDC motor and using various thread configurations, this actuator can be designed for various loads and speeds to suit various applications.

REFERENCES TO THE DRAWINGS AND PICTURES

Drawing 1 shows the cross-sectional view of the linear actuator.

Drawing 2 shows the linear actuator when viewed from the end of the anti-rotating shaft.

Drawing 3 is a close-up view of the anti-rotating shaft with anti-rotational cross-section inside the hole of the mounting plate that has a matching anti-rotation profile.

Drawing 4 shows the lead screw that is threaded at one portion and an anti-rotational shaft at the other portion.

Drawing 5 shows the anti-rotation hole feature on the mounting plate.

Drawing 6 shows the tach pattern on the printed circuit board.

Pictures 1 and 2 shows the external view of the reciprocating linear actuator with the main components labeled.

Picture 3 shows the sectional view of the linear actuator.

Picture 4 is a view of the hall effect sensor mounted at the rear of the actuator.

Picture 5 shows the part of the lead screw that is shaped to prevent rotational movement.

Picture 6 shows the wires connecting the hall effect sensor to the microcontroller PC board.

Picture 7 shows the actuator with the enclosure removed.

Picture 8 shows the enclosure with the hall effect sensor mounted.

Picture 9 shows the rotor with the hollow spindle and tach magnet.

Picture 10 shows the motor driver printed circuit board

Picture 11 shows the layout of the magnetic poles around the tach magnet.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following description below describes the best mode presently utilized for producing the invention for industrial use. They will be described in detail with references to drawings 1 through 6.

BLDC Motor

This invention refers to a linear reciprocating actuator driven by a conventional outside-spin brushless DC motor. The motor has a revolving rotor ², a stationary stator ⁴ and a printed circuit board (PCB) ⁵ containing the drive and microcontroller electronics.

Hollow Spindle

A hollow spindle ⁸ with an internal thread ⁶ is attached to the rotor. The hollow spindle is made from metal. The internal thread is molded out of engineering plastic such as glass reinforced PBT (polybutylene terephthalate) or PA46 (polyamide 4/6) that is able to withstand the high physical forces and temperatures. The rotor is then mounted to the stator riding on two ball bearings ¹⁵.

Lead Screw

The lead screw (drawing 4) is made up of two different types of shafts, the threaded shaft ⁹ and the anti-rotating shaft ¹⁰. One end of the threaded shaft has a recess that will facilitate the assembly of the sensor magnet ¹¹. The anti-rotation shaft has a cross-section that is shaped such that it can prevent rotational motion when fitted through with a stationary matching hole. This hole is found on the mounting plate which is explained later. An attachment feature is made at the end of the anti-rotation shaft that will be used to attach to the driven device. Examples of attachment features are screw threads (externally or internally threaded) and hooks. The two shafts can be made from one solid metal piece or joined together either by interference fit, adhesives, screw or any other method that is strong enough to hold the two parts together. The holding strength must be greater than the maximum linear force of the actuator. The 2-pole sensor magnet is attached to the end of the threaded portion via adhesives.

Mounting Plate

The mounting plate ¹², which is attached to the stator is made of metal and has two mounting holes at each end of the plate which are used for mounting the linear actuator onto the device that it is driving. A hole ¹³ with a shape that matches the anti-rotation shaft ¹⁰ is made at the area where the lead screw protrudes out from the actuator body.

The Position Feedback System

A ring-shaped tach magnet ⁷ that has been pre-magnetized with poles around it (picture 11) is attached to the rotor just above a tach pattern ¹⁶ that is imprinted on the PCB. The tach pattern provides generates electric pulses when the magnetic fields from the tach magnet cuts through them when the rotor is rotating.

To place the hall sensor ¹⁴ at the rear end of the actuator, some kind of stationary mounting device is required. One possible method is to have a metal enclosure that envelops the whole rotor (picture 1) and secured to the mounting plate. A small printed circuit board sits at the top of the enclosure (picture 4, 8) secured by two screws. The position hall sensor is soldered to this PC board and positioned at the end of the retracting stroke of the lead screw. When the sensor magnet ¹¹ attached to the each of the lead screw moves past the hall sensor, the change in the magnetic polarity toggles the hall sensor which then provide a feedback to the microcontroller. Besides providing a mounting surface for the hall sensor, the enclosure also functions as a safety device that prevents human contact with the spinning rotor. Slots around the enclosure allow for air ventilation around the motor. The sensor board is then connected to the microcontroller board with wires. These wires carry the signal from the hall sensor to the microcontroller. The microcontroller board, which contains the pre-programmed microcontroller chip and its supporting electronic devices (picture 6) is connected directly to the motor drive board. The main power input terminals are also found in this board.

Stroke Correction Methodology

This method was developed to correct “shaft overshoot” and “shaft underrun”. Shaft overshoot is caused by rotor inertia which makes the shaft travel a little further than designed stroke before the rotor comes to a complete stop and reverses its direction. Both shaft overshoot and underrun (i.e.: actual stroke shorter than designed stroke) are caused by a load that is varying in magnitude. One example of this kind of load is the vacuum pump where the vacuum pressure (load) is built up over time as more and more air is pumped out. The correction methodology is described as follows.

Upon power-up, the microcontroller is programmed to retract the shaft. When the shaft reaches the retracted end for the first time, the sensor magnet toggles the hall effect sensor. The microcontroller sets the tach count to zero at this instance and the motor direction is switched to rotate in the opposite direction. This cause the lead screw to move away from the sensor (extend stroke). As the motor rotates and extending the shaft, the microcontroller keeps track of the stroke distance by counting the pulses generated by the tach magnet. Each revolution of the rotor produces a fixed number of tach pulses. When the pulse count reaches a preset value, the microcontroller commands motor to stop. This preset value corresponds to the designed stroke length of the actuator. For example, assume that the tach magnet has 45 pairs of magnetic poles that generates 45 pulses per rotor revolution, and the threaded shaft of the lead screw has a pitch of 2.44 mm (i.e.: the shaft moves forward/backward by this amount in one rotor revolution). If the required stroke length is 18.21 mm, then the number of pulses generated by the tach magnet during the entire stroke traverse is

$$18.21 \div 2.44 \times 45 = 336 \text{ pulses}$$

This will be the preset value.

When the pulse count reaches 336, the microcontroller sends the stop signal to the motor. However, due to inertia the rotor does not stop instantly when commanded to stop. It will continue to rotate while slowing down at the same time. During this deceleration time the microcontroller keeps on counting the tach pulses until the rotor comes to a complete stop.

The difference between the actual number of tach pulses and the preset value represents the overshoot. The overshoot value is subtracted from the preset value and this result will be used as the “pulse count” in the next extension stroke. Basing on the previous example, assume that the shaft overshoots the intended position when it first extends and the microcontroller computes the overshoot value to be 67 pulses (i.e.: 67 pulses beyond the designed 336). Therefore, the pulse count for the next extension stroke will be

$$336 - 67 = 269 \text{ pulses}$$

At the next extension stroke, the motor will be commanded to stop when the pulse count reaches 269. Since this value is smaller than the preset value, the motor will be commanded stop before the end of the actual stroke. Like before, inertia will cause the rotor to spin a little longer and will finally come to a complete stop at the desired position.

In some applications, the load is not constant but changes over time and this will also affect the stroke length. One characteristic of the BLDC motor is that its torque changes with the load. A heavy load will slow the motor down and vice versa. In the linear actuator, this attribute causes the stroke length to vary with the load. A load that has changed in magnitude from the previous stroke will affect the rotor deceleration time. Back to our earlier example, assume that the load has increased this time round and the rotor comes to a complete stop at pulse count 329 (Note: it would have been 336 if the load were constant). This is 7 counts less than the preset count of 336. This variation will be added to the pulse count (currently 269), making the new pulse count value equal to

$$269 + 7 = 276 \text{ pulses}$$

This correction is repeated each time at the end of every extension stroke. With this method, stroke length deviation caused rotor inertia or varying load is virtually eliminated.

Other Features

The actuator has a safety protection feature that switches the motor off there is an overload, i.e. when the load is above the capacity of the motor. An overload will cause the motor to produce much heat due to the increased current running into the coil winding. In the extreme case, the motor will stall and the increased heat may cause the motor coils to burn. This safety feature is accomplished by adding codes to the firmware which analyzes the tach pulses from the motor. If the motor is commanded to rotate but there are no tach pulses after a certain time, a time-out is enabled that switches off the motor.

CLAIMS

What is claimed is:

1. A linear reciprocating actuator ¹ comprising a brushless direct current (BLDC) motor, lead screw ³, hollow spindle ⁸, mounting plate ¹² and position feedback system.

The BLDC motor of the said linear actuator comprising:

- a rotor ²
- a stator ⁴
- drive electronics mounted on a printed circuit board ⁵

The lead screw ³ of the said linear actuator comprising:

- an externally threaded shaft ⁹ which is mated with the internal thread of the hollow spindle ⁸
- an anti-rotating shaft ¹⁰ with a cross-section shape that prevents rotational motion when fitted through a matching stationary hole ¹³

Both the externally threaded shaft and the anti-rotating shaft are joined together to become a single component.

The hollow spindle ⁸ of the said linear actuator having an internal thread ⁶ that matches the externally threaded shaft ⁹ of the said lead screw. The hollow spindle is attached to the said rotor ² along its axis of rotation such that when the rotor rotates, the internal thread converts the rotational motion into linear movement of the lead screw.

The mounting plate ¹² of the said linear actuator having a hole ¹³ whose shaped matches the cross-sectional shape of the anti-rotating shaft ¹⁰ of the said lead screw. The anti-rotating shaft ¹⁰ of the lead screw fits through this hole.

The position feedback system of the said linear actuator comprising:

- a tach magnet ⁷ attached to the said rotor ²
 - a sensor magnet ¹¹ attached to the end of the threaded shaft ⁹ of said lead screw
 - a hall effect sensor ¹⁴ that is placed in a fixed position where the said sensor magnet can toggle its digital state when the said lead screw approaches the retracted end of the stroke
 - a tach pattern ¹⁶ imprinted on the said printed circuit board ⁵
 - a programmable microcontroller
2. A method of fabricating the linear actuator defined in claim 1 that consists the steps of:
- making an internal thread inside the hollow spindle ⁸
 - attaching the sensor magnet ¹¹ to the end of the lead screw
 - mounting the hall effect sensor ¹⁴ at the retracted end stroke of the lead screw
3. The method of dynamically correcting the actual stroke length of the linear actuator defined in claim 1 to the designed stroke length by using the tachometer pulses in the form of an algorithm stored inside the microcontroller defined in claim 3.
4. The method of sensing the complete stop of the said rotor of the linear actuator defined in claim 1 by checking the absence of tachometer pulses at the end of each extended and retracted stroke in the form of an algorithm stored inside the microcontroller defined in claim 3.
5. The method of sensing overloads to the linear actuator defined in claim 1 by checking the absence of the tachometer pulses during each stroke traverse not including the end of each stroke and turning the motor off in the form of an algorithm stored inside the microcontroller defined in claim 3.