Creating Linear Motion One Step at a Time

In classic mechanical engineering, linear systems are typically designed using conventional mechanical components to convert rotary into linear motion. Converting rotary to linear motion can be accomplished by several mechanical means using a rotary motor, rack and pinion, belt and pulley, and other mechanical linkages, which require many components to couple and align. Although these methods can be effective, they each carry certain limitations. Conversely, stepper motor-based linear actuators address all these factors and have fewer issues associated with their use. The reason? Rotary-to-linear motion is accomplished in the motor itself, which translates to fewer components, high force output, and increased accuracy.

What Is a Stepper Motor-Based Linear Actuator?

A linear actuator is a device that develops a force and a motion through a straight line. A stepper motor-based linear actuator uses a stepping motor as the source of rotary power. Inside the rotor there's a threaded precision nut instead of a shaft; the shaft is replaced by a precision leadscrew. As the rotor turns (as in a conventional stepper motor), linear motion is achieved directly through the nut and threaded screw. It makes sense to achieve the rotary to linear conversion directly inside the motor, as this approach greatly simplifies the design of rotary-to-linear applications. This creates mechanical advantage, high resolution, and accuracy ideal for use in applications where precision motion is required.

Basic Components: the Stepper Motor

Why use a stepper motor instead of a conventional rotary motor? Unlike other rotary motors, steppers are unique in that they move a given amount of rotary motion for every electrical input pulse. This makes steppers a perfect solution for use in positioning applications. Depending on the type of stepper motor, they can achieve resolutions from 15 rotational degrees per step to 0.9 rotational degrees per step. This unique "stepping" feature coupled with the characteristics of the lead screw provides a variety of very fine positioning resolutions.

How Does the Stepper Motor Work?

Permanent magnet stepper motors incorporate a permanent magnet rotor, coil windings, and a steel stator capable of carrying magnetic flux. Energizing a coil winding creates an electromagnetic field with a NORTH and SOUTH pole. The stator conducts the magnetic field and causes the permanent magnet rotor to align itself to the field. The stator magnetic field can be altered by sequentially energizing and de-energizing the stator coils. This causes a "stepping" action and incrementally moves the rotor resulting in angular motion.

"One-Phase On" Stepping Sequence

Figure 1 illustrates a typical step sequence for a simplified two-phase motor. In Step 1, phase A of the two-phase stator is energized. This magnetically locks the rotor in the position shown, since unlike poles attract. When phase A is turned off and phase B is turned on, the rotor moves 90° clockwise. In Step 3, phase B is turned off and phase A is turned on but with

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the polarity reversed from step 1; this causes another 90° rotation. In Step 4, phase A is turned off and phase B is turned on, with polarity reversed from Step 2. Repeating this sequence causes the rotor to move clockwise in 90° steps.
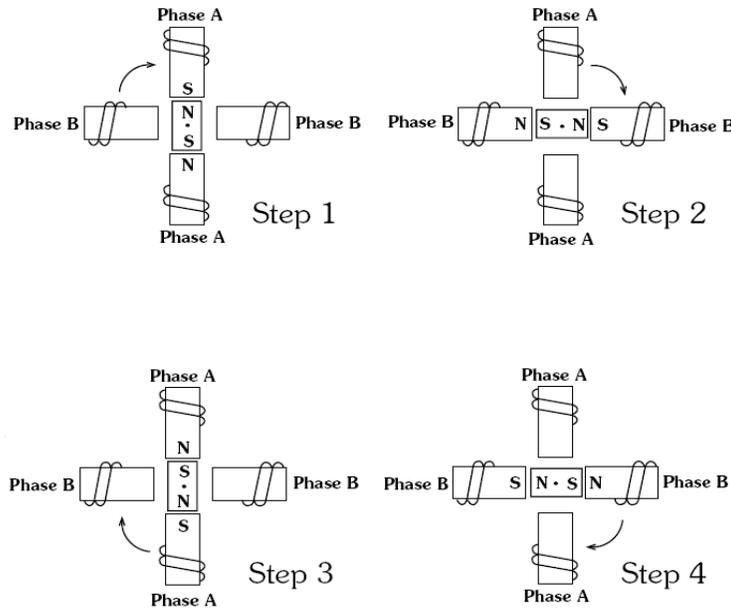

Figure 1. "One-Phase On" stepping sequence for two phase motor

"Two-Phase On" Stepping Sequence

A more common method of stepping is "two-phase on" where both phases of the motor are always energized. However, only the polarity of one phase is switched at a time, as shown in *Figure 2*. With two-phase on stepping, the rotor aligns itself between the "average" north and "average" south magnetic poles. Since both phases are always on, this method provides 41.4% more torque than "one-phase on" stepping.
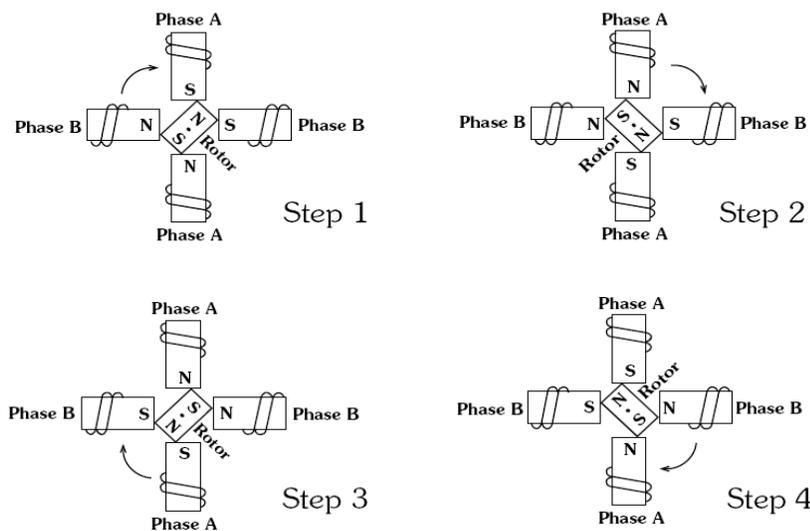

Figure 2. "Two Phase On" stepping sequence for two phase motor

Basic Components: the Lead Screw

The lead screw is a special screw that provides a linear force using the simple mechanical principle of the inclined plane. Imagine a steel shaft with a ramp (inclined plane) wrapped around it; the mechanical advantage (force amplification) is determined by the angle of the ramp - a function of the lead, pitch, and screw diameter.

- **Lead** – The axial distance a screw thread advances in a single revolution.
- **Pitch** – The axial distance measured between adjacent thread forms.
- **Number of Starts** – The number of independent threads on a screw form optimized for manufacturability.

The relationship of "lead" to "pitch" depends on the "number of starts" and is expressed in the following equation. For a single start thread, the lead is equal to the pitch.

lead = (pitch) x (number of starts)

The threads of the lead screw allow a small rotational force to translate into a large load capability depending on the steepness of the ramp (the thread lead). A small lead will provide a high force and high resolution output. A large lead will provide a lower force, but a correspondingly higher linear speed from the same source of rotary power.

Pictured above are several examples of different thread configurations

Basic Components: Integrated Nut

Of equal, if not greater importance to the lead screw is the nut that drives the screw. This nut is often imbedded in the rotor of the stepping motor, which makes this actuator configuration unique from other rotary to linear techniques. The traditional nut material is a bearing grade bronze which lends itself to the required machining of the internal threads. Bronze is a compromise between physical stability and lubricity. Compromise, however, is the key word since it excels at neither.

Friction Considerations

A much better material for a power nut in the linear actuator is a lubricated thermoplastic material. With the evolution of new engineered plastics, the nut/screw thread interface can now exhibit a much lower coefficient of friction when compared with the traditional bronze nut material. In fact, a change from bronze to an engineered thermoplastic for the

nut threads results in a friction reduction of approximately 45%. This results in a higher-efficiency system while allowing a smaller motor footprint for the same amount of force output.

Thermal Considerations

Given the data, it is clear that a plastic drive nut provides the lower coefficient of friction when compared with bronze. Unfortunately, as good as the plastic is for threads, it is not stable enough for the bearing journals of a hybrid stepper motor, which are critical in the motor design. Under a continuous full-load condition, plastic bearing journals can expand as much as four times compared to brass journals.

In order to achieve the high performance characteristics of the stepper motor, the design must maintain a stator-to-rotor airgap of only a few thousandths of an inch. This tight design requirement demands thermally stable bearing journals. By injection-molding plastic threads within a brass rotor assembly, characteristics of low friction and high bearing journal stability are achieved (*Figure 3)*, resulting in a product with quiet operation, higher efficiencies, and higher life expectancies. In fact, motor life is improved by 10 to 100 times over the traditional bronze nut configuration.
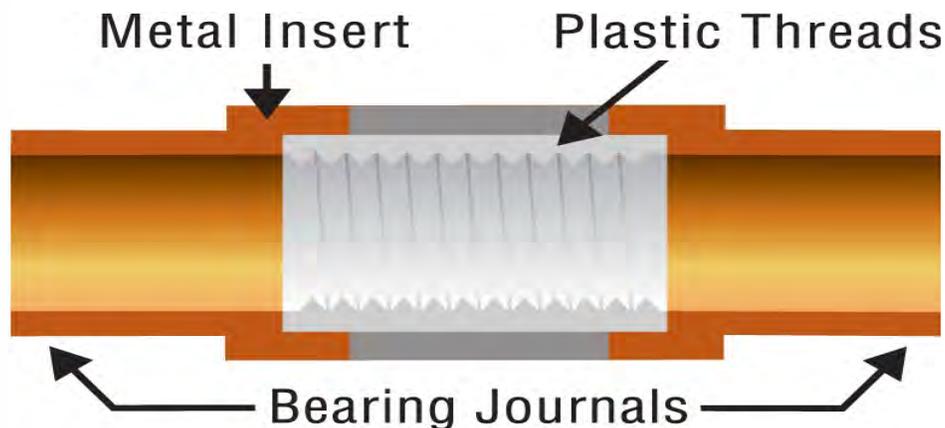

Figure 3. Power Nut Configuration – Embedded in Permanent Magnet Rotor

Putting It All Together

By combining all components as explained above, the stepper motor-based linear actuator is created. *Figure 4* is a schematic of a "captive" type linear actuator. Captive indicates that there is already an anti-rotation mechanism built into the actuator through the use of a splined "anti-rotation" shaft and a "captive sleeve." The "captive" configuration is ideal for use in precision liquid drawing/dispensing and proportional valve control. Other forms of linear actuators are "non-captive" and "external linear" as pictured in *Figures 5* and *6.*
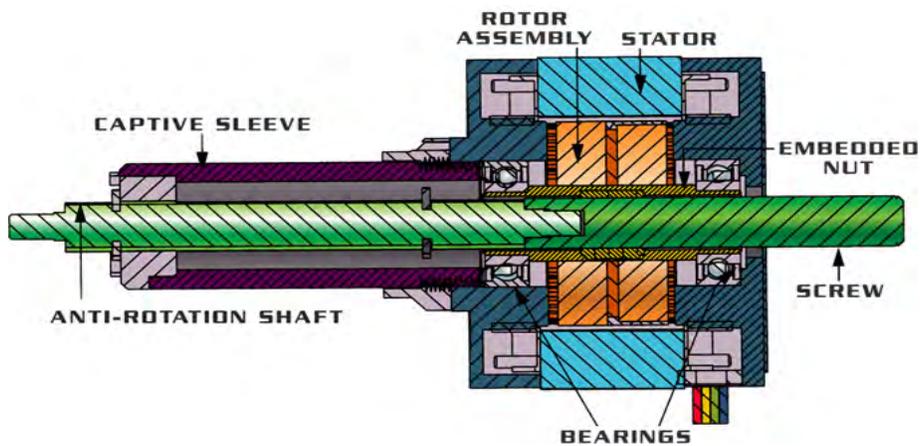
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Figure 4. Section view of a hybrid captive linear stepping actuator

Hybrid Captive **Hybrid Non-Captive** **Hybrid External Linear**

Figure 5. Hybrid Linear Actuators: 1.8 and 0.9 Rotational Degrees/Step

Canstack Captive **Canstack Non-Captive** **Canstack External Linear**

Figure 6. Canstack Linear Actuators – 15 and 7.5 Rotational Degrees/Step