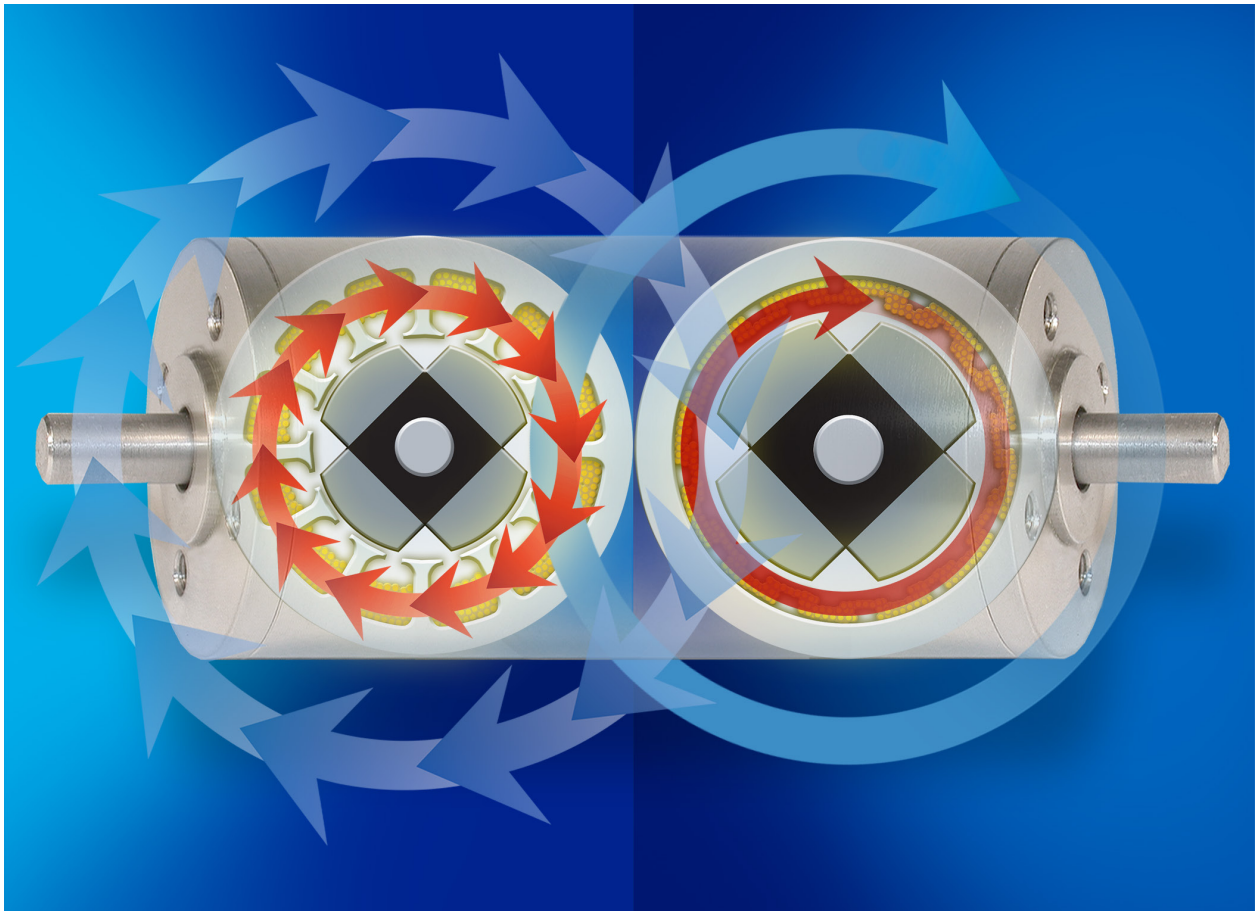
COMPARING SLOTTED vs. SLOTLESS BRUSHLESS DC MOTORS



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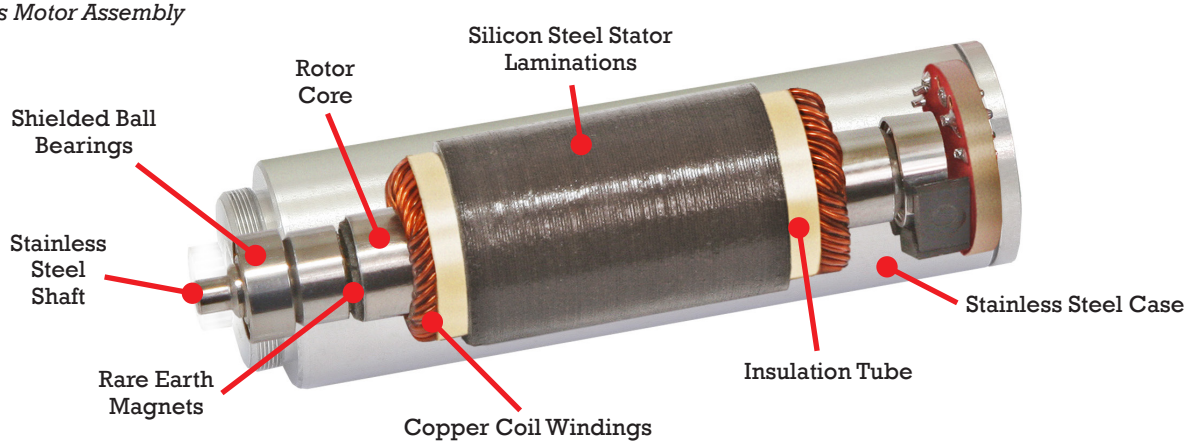
Slotless brushless DC motors represent a unique and compelling subset of motors within the larger category of brushless DC motors. They are called "slotless" because typical slotted brushless DC motors contain a stator core of laminated steel composed of slots separated by teeth around which copper wire is wound. The windings in slotless motors are made possible by specialized winding process technology, such as the Parallex windings offered by PITTMAN. Motors featuring these windings offer several benefits such as low cogging, low vibration and low noise enabling smooth operation, as well as reduced rotational losses enabling higher speeds with reduced heating. These characteristics are especially advantageous in applications requiring high power output in an ergonomic design, such as high-power hand-held devices like surgical tools.

Construction

Most brushless motors (slotted or slotless) utilize a rotating permanent magnet rotor assembly surrounded by fixed windings. The motor's rotor assembly consists of a steel shaft with permanent magnets, or magnetic ring, secured around the circumference of the shaft. The magnets produce a magnetic field which interacts with the field produced by the windings. Torque is produced as the product of the forces applied to the magnet, times the moment arm at which it is applied. The level of torque can thus be affected by many factors, including magnet strength, distance between opposing magnetic fields, winding or stator field strength and the distance from the motor center to field interaction. See Figure 1 for a cutaway view of a slotless brushless DC motor.

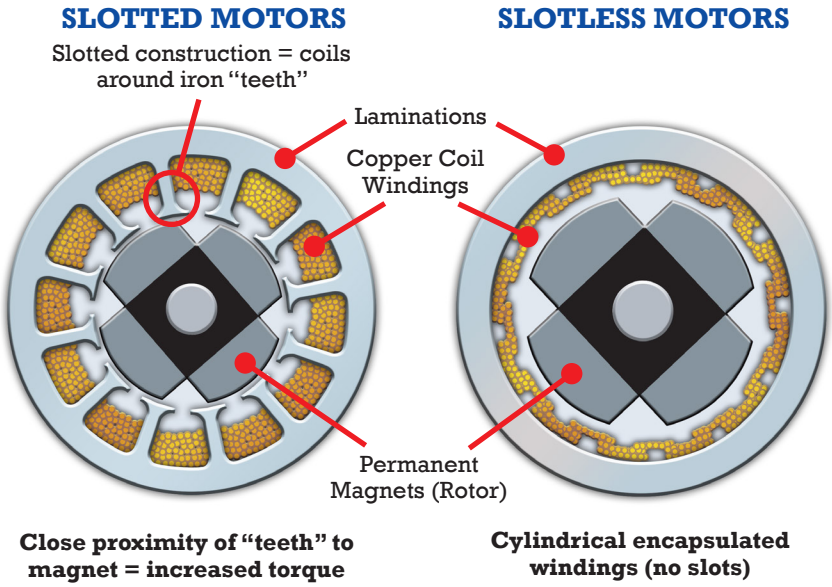
In traditional slotted brushless motors, the stator features a group of flat electrical steel laminations, typically on the order of 0.5mm thick each, which are assembled to form a solid stack. The outer section of each lamination contains a ring of material from which a pattern of teeth project toward the inside. Copper coils, which produce electromagnetic fields when current is passed through them, are then wound around the teeth or inserted into each of the slots between the teeth. The laminated stack and wound copper coil form the stator assembly. The return path completing the magnetic circuit consists of the laminated material outboard of the copper windings in the stator. See section of Figure 2 titled "Slotted Motors" for an axial section view of a slotted stator.

Fig. 1 Slotless Motor Assembly



Instead of winding copper coils through slots in a laminated steel stack as in conventional slotted brushless motors, slotless motor coils are wound into a cylinder, and the coils formed and adhered to maintain their shape. In the case of the PITTMAN Parallex motors, this is accomplished by a proprietary method involving winding the wire into carefully designed coils that are precisely formed and inserted into a laminated stack that is similar to that of a slotted motor except that the laminations are simple rings without teeth (and therefore "slotless"). See section of Figure 2 titled "Slotless Motors" for an axial section view of a slotless stator.

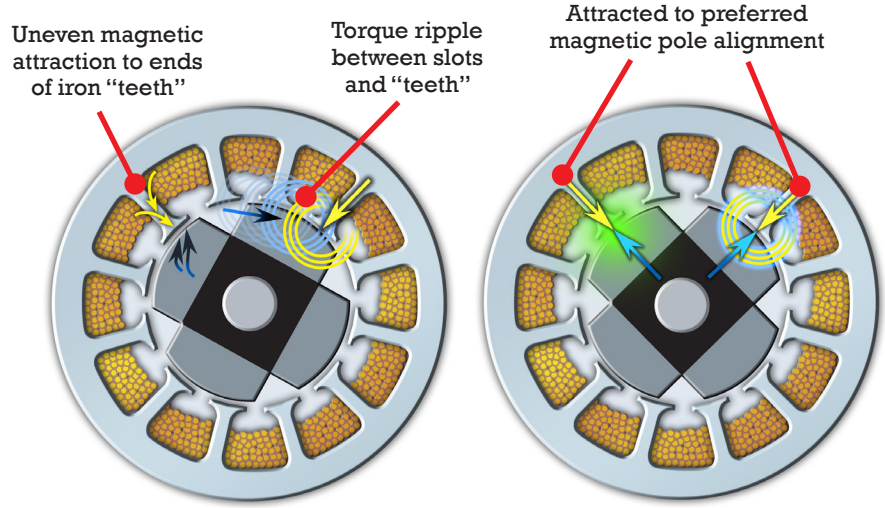
Fig. 2 Comparison of Slotted vs. Slotless Motors



Features and Benefits

Slotted brushless motors are especially powerful because the teeth around which the copper coils are wound place the iron closer to the magnets. In this way the air gap is minimized and the magnetic circuit is completed more efficiently. As the air gap between iron and magnets is reduced, the potential torque produced by the motor is increased. However, slotted stators are known to cause cogging due to the teeth in their construction. Cogging occurs when the permanent magnets on the rotor seek a preferred alignment with the teeth and slots of the stator. Winding copper coils through the slots tends to increase this effect. As magnets pass by the teeth, they have a greater attraction to the iron of the teeth than to the air gaps between them. This uneven magnetic pull causes the cogging, which ultimately contributes to torque ripple, efficiency loss, motor vibration and noise, as well as prevents smooth motor operation at slow speeds. See Figure 3 for an illustration of cogging in a slotted motor.

Fig. 3 Slotted Motor Clogging Effects



A slotless stator offers a solution to the problems experienced with cogging in slotted brushless DC motors. This configuration, which excludes the stator teeth, eliminates cogging altogether and results in desired quiet operation and smooth performance. Because the slotless design has no stator teeth to interact with the permanent magnets the motor does not generate detent torque.

PITTMAN Parallex technology allows construction of compact windings that would be much more difficult to achieve in the space and configuration available in a slotted structure,

facilitating ever smaller motor sizes. A distinctive aspect of the Parallex technology compared to other slotless winding methods is that the magnet wire of the copper coils is routed in a straight path through the active length of the lamination stack parallel to the rotor axis and magnets, maximizing torque production.

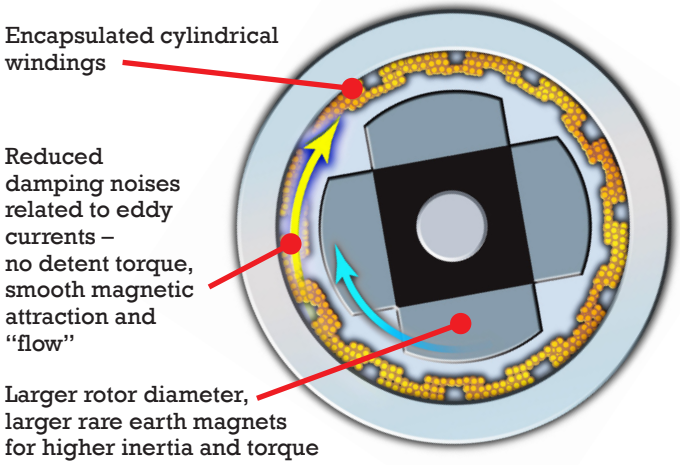
The slotless design also reduces damping losses related to eddy currents, which are circulating currents created in the laminations due to the changing magnetic fields. These currents produce losses which increase with rotational speed and manifest themselves as heat. Eddy currents are weaker in a slotless motor because there is less lamination material and the distance between the laminated iron and magnets is greater than in a slotted motor.

Slotless motors are typically designed with sinusoidal torque output that produces negligible distortion, rather than a trapezoidal voltage output. The sinusoidal output reduces torque ripple, especially when used with a sinusoidal driver. In addition, low magnetic saturation allows the motor to operate at several times its rated power for short intervals without perceptible torque roll-off at higher power levels.

Compared with slotted motors, slotless construction also can significantly reduce inductance and electrical time constant to improve current bandwidth. The teeth in a slotted motor naturally cause more inductance since the coils of copper wire around the teeth interact with the iron in a slotted motor. This interaction tends to send the current back on itself, resulting in more damping (or dragging) and impacting negatively on slotted motor response and acceleration.

One more important difference between slotless and slotted designs is the rotor diameter. Slotless motors typically have a larger rotor diameter than slotted construction for the same outside motor diameter. This results in greater rotor inertia as well as more magnet material for greater torque. For applications with high-inertia loads the slotless product is more likely to be specified. See Figure 4 for an illustration of characteristics of slotless motors.

Fig. 4 Slotless Motor Smoothness



In terms of delivering power, conventional slotted motors used to enjoy the advantage over slotless types due to the proximity of iron and magnets and the reduced air gap. However, this advantage has virtually evaporated in large part due to the utilization of high-energy, rare earth magnets (such as samarium cobalt and neodymium iron boron). By incorporating these magnets, manufacturers of slotless brushless motors have been able to routinely compensate for the greater air gap distance. These more powerful magnets effectively enable the same (or better) torque performance for slotless products compared with slotted. Eliminating the teeth and using stronger magnets both serve to maximize the strength of the electromagnetic field for optimum power output. Rare-earth magnets, along with the fact that fewer coils, or "turns," of the wire are required in slotless motors, also help contribute to low electrical resistance, low winding inductance, low static friction, and high thermal efficiency in slotless motor types.

Applications and Markets

In general, brushless motors are usually selected over brush-commutated motors for their extended motor life. Other reasons for specifying brushless motors include a wide speed range, higher continuous torque capability, faster acceleration, and low maintenance.

In particular, slotless brushless DC motors will suit those applications that require precise positioning and smooth operation. Typical niches for these

motors include computer peripherals, mass storage systems, test and measurement equipment, and medical and clean-room equipment. The unique characteristics of PITTMAN Parallex technology are particularly advantageous for surgical hand tools that require high power output in a small size while minimizing temperature rise.

As further examples, designers of medical equipment can utilize slotless motors for precise control in machines that meter and pump fluids into delicate areas, such as eyes. In medical imaging equipment, slotless brushless DC motors decrease banding by providing smoother operation at low speeds. Airplane controls supply smoother feedback to pilots. By eliminating cogging and resulting vibration, these motors can reduce ergonomic problems associated with hand-held production tools. Other appropriate applications include scanners, robots for library data storage, laser beam reflector rotation and radar antenna rotation equipment, among many others.

Product Range, Sizing, and Selecting

Despite the overall design and performance comparisons reviewed here for slotless and slotted brushless DC motor types, one should remain cautious in drawing any conclusion that one type is the ultimate choice over the other. There are simply too many variables that must be evaluated, ranging from rotor size and windings to housing and special components. A given application and its requirements should be the guiding factors in selecting a particular motor type and the customized components to be incorporated.

Due to their more complex design and coil forming processes, slotless motors are generally more costly than their slotted counterparts. Regardless of any cost differential, slotless brushless DC motors will be the preferred choice to resolve specific requirement issues for many applications. While advances in electronics continue to be applied that promise to reduce normal cogging in slotted products as a step toward making these motors more smooth-running and quiet, slotless motors remain the best alternative where cogging and life are defining performance issues.

General sizing and selecting for slotless brushless DC motors is similar to that for other motors, and is a function of requirements including: load torque and speed, available voltage and current, size and weight constraints, duty cycle, and environmental conditions. The following table highlights the basic PITTMAN Parallex slotless brushless DC motor offering:

Series	Diameter	Torque	Maximum Recommended Speed
ES010A (BI-04)	0.375 in (9.5 mm)	0.3 oz-in (0.002 Nm)	80,000
ES013A (BI-05)	0.5 in (12.7 mm)	0.9 - 1.1 oz-in (0.006 - 0.007 Nm)	60,000
ES020A (BI-08)	0.8 in (20 mm)	1.8 - 4.3 oz-in (0.012 - 0.03 Nm)	50,000
ES028A (BI-11)	1.1 in (28 mm)	6.2 - 14.9 oz-in (0.043 - 0.11 Nm)	20,000
ES030A (3400)	1.38 in (35 mm)	4 - 5.8 oz-in (0.028 - 0.040 Nm)	8,000
ES040A (4400)	1.65 in (42 mm)	12 - 19 oz-in (0.08 - 0.13 Nm)	8,000
ES050A (5400)	2.28 in (58 mm)	25 - 43 oz-in (0.176 - 0.30 Nm)	5,000

Differentiators and Options

PITTMAN slotless brushless DC motors feature an offering of standard platform designs that can be customized to meet specific performance and application requirements. As examples, spur gearheads can be integrated on motors for an application's specific torque and cost requirements while planetary gearheads offer a higher speed and torque alternative. Slotless motors can be customized further with optical encoders, which provide accurate position, velocity, and direction feedback that greatly enhances motor control and allows the motors to be utilized in a wider range of applications.

Because PITTMAN Parallex technology is so particularly well-suited to small hand-held surgical devices, one of the most salient options available is autoclavability. This provides the medical device designer with inherent protection for the motor in applications requiring steam sterilization. Autoclavable motor designs are tailored to specific customer requirements and include a variety of specialized materials and processes to meet the harsh demands of these applications.

Other options that can be selected and customized for particular applications include Halls sensors or sensorless design, balanced rotors, connectors, custom cables, shaft modifications, shaft-mounted pulleys and gears, special bearings and windings, and electromechanical brakes. Each can deliver specific performance benefits and ensure application requirements are satisfied.

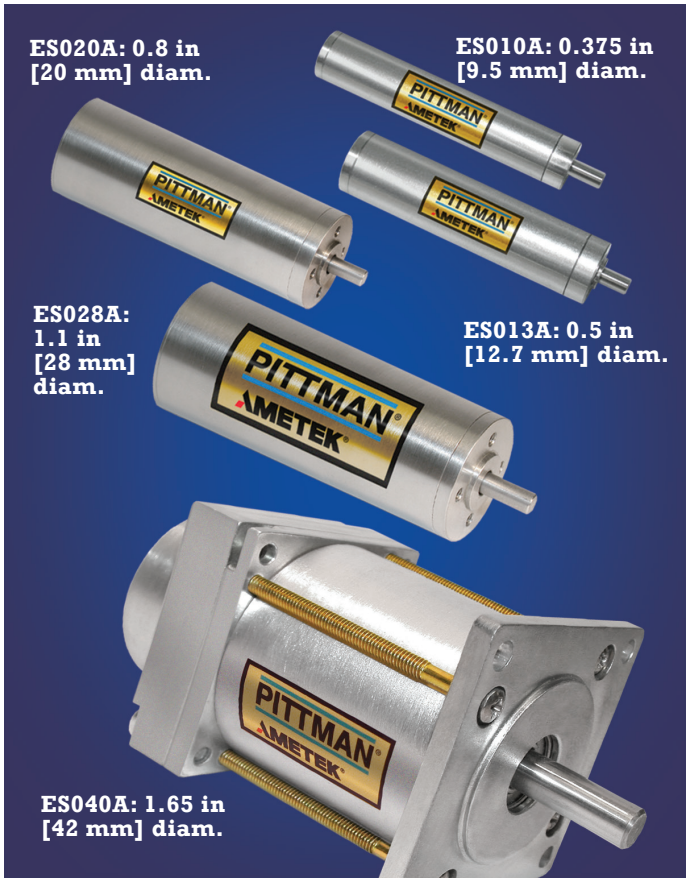


Fig. 5 PITTMAN Slotless Motor Products (also available – ES30A: 1.38 in [35 mm] diam. and ES050A: 2.28 in [58 mm] diam.

This technical presentation was prepared by the engineering team at PITTMAN, a leader in brush and brushless DC motor technologies. Complex custom and ready-to-ship standard made at U.S. facilities with a full range of on-site capabilities including designing, engineering and manufacturing.

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