Introduction to SEMA Motor Technology

June 2005

A unique architecture for permanent magnet electric motors and controllers, based on the Segmented ElectroMagnetic Array (SEMA), is being proposed for electric motor and actuator applications requiring high power density and high efficiency. This electric motor design methodology is based on recent advances in materials, computer aided design, control, and a new appreciation for certain principles of electromotive physics. SEMA motor and controller technology is being developed by Kinetic Art & Technology Corporation and commercialized by Lynx Motion Technology Corporation.

Many applications may benefit from or require a motor drive with high power density and very low torque ripple. These include precision motion control, naval propulsion systems, and acoustically sensitive applications. However, conventionally designed motors often lack the required power density or possess magnetic characteristics that inherently produce low frequency torque oscillations and acoustical noise. In particular, the slotted magnetic core in such machines introduce cogging, magnetic saturation, armature reaction, and hysteresis phenomena which all contribute to this effect. Furthermore, even in the absence of such phenomena, any non-sinusoidal nature to the motor's field distribution will also create low frequency torque pulsations unless custom-designed current commutation waveforms are used.

Since 1994, Lynx Motion Technology and its parent company, Kinetic Art and Technology, have been developing a high power density motor technology called the Segmented ElectroMagnetic Array (SEMA). This technology is based on an axial gap (disk) motor topology that uses a unique coil design along with innovative manufacturing techniques to produce a motor with significantly improved specific power over competitive machines, while being very economical to produce.

Motors based on SEMA architecture may be operated at constant or variable speed, steady state or intermittently, and can be reversed, with excellent performance in all modes. Since there is no cogging – even at low speeds – power is delivered to the motor in a quiet, continuous manner. Many power sources can be

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used as input to the motor's power electronics, including direct current or single- or three-phase alternating current. Under computer control, the motor can be controlled precisely in torque and speed, and can be positioned with high accuracy and repeatability. There are no brushes or contacts to malfunction or wear, spark, or cause losses inside the motor. The SEMA motor's unique stator construction reduces wire resistance losses and eliminates iron saturation and hysteresis losses. The inherent modularity and scalability of SEMA technology facilitates configuration of motor components to support a wide variety of applications. This allows a wide range of motors to be produced from a small set of mass-produced components.

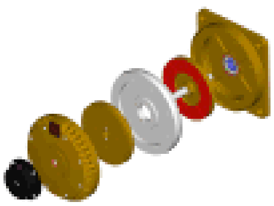
In addition to enabling electric motor systems of unprecedented power density and controllability, SEMA technology is being commercialized for electric generators and may have a significant impact on the performance of energy storage systems, such as flywheel motor/generator systems.

SEMA-based motor designs may be implemented with conventional housings and output shafts as well as in custom configurations. These motors are structurally equivalent to their conventional counterparts, interchangeable in many applications, yet lighter, quieter, more powerful and more efficient. These motors can operate at high, medium, and low speeds, including stall, with constant torque across the speed range.

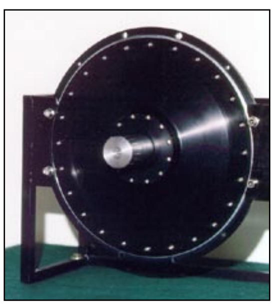
The SEMA motor's extremely high torque and efficiency make it practical as a direct-drive motor in applications which usually require a speed reducer. This application eliminates gear noise, positioning errors from backlash (common in gear drives), and lack of torsional stiffness (common in harmonic drives), yielding a quieter and smoother system. Since precision speed reducers or conversions to hydraulic actuation often cost much more than the motors which drive them, motor systems using SEMA-based electric motors may also offer a cost savings over non-direct drive motors.

While many of the SEMA's attributes recommend it for use in electric drives, it is its uniform production of torque that makes this motor technology inherently quiet. Two major attributes of the SEMA yield this result: First, the production of torque within the SEMA motor remains proportional to current. Second, the motor's torque is uniform with respect to rotor position.

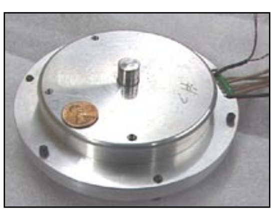
7" and 14" SEMA motors built by Bodine Electric (*http://www.e-torq.com*)



Exploded view of a standard 7" TENV flange style motor (*http://www.e-torq.com*)



Lynx T468 SEMA motor



Configurability

SEMA-based designs may be configured around several unique coil structures and magnetic circuits, all of which have been developed with increased torque and efficiency in mind. These make possible SEMA configurations for conventional three-phase designs as well as more advanced multiphase designs and architectures requiring complex, customized control implementations. The versatile control potential of SEMA motors owes much to these coil designs. Advanced control opportunities that may be explored in future research include the ability to generate real-time commutation waveforms, intelligent control modules directly integrated into the motor, and the ability to configure a SEMA device as both a motor and generator in systems incorporating power management schemes.

Custom 14" hub-style TENV motor built to power a solar race car (*http://www.e-torq.com*)

SEMA Cost and Manufacturing

One of the most attractive features of this new technology is its compatibility with existing motor technology. The simplicity of SEMA construction makes it possible to manufacture many variations of the design with conventional manufacturing techniques for electric motors. A SEMA-based motor, despite its high power density and efficiency, may be brought to market at a cost equal to the cost required to implement a conventional design. As high-volume production techniques are employed, the cost of SEMA motors should become lower than their conventional counterparts.

SEMA-based generator system

Maturity of Technology

To date, this technology has been supported by several federal research contracts (through DARPA, NASA, and the Department of Energy) and private investment, resulting in considerable progress in validation of the fundamental concepts. Testing of motors has confirmed the expected torque-generating characteristics of the SEMA magnetic circuit and has thus far confirmed the anticipated degree of precision control. SEMA motor products are being sold into the servo motor market by Bodine Electric Co.

Technical Progress to Date

Under DARPA, DOE, and investor funding, several prototype motors have been designed, constructed, and tested. These include:

Custom 7" SEMA motor from Bodine Electric (*http://www.e-torq.com*)

- A servo motor acting as axis 1 of an industrial welding robot; motor has been through over one million cycles of endurance testing (near-continuous operation over a one and one half year period
- Constant velocity motors manufactured by Bodine Electric under license from Lynx for various commercial applications
- A medium-speed motor/alternator designed and built under a DOE contract by Delco Remy for the FutureTruck program
- Motors for autonomous underwater vehicle (AUV) operation under contract with Pennsylvania State University's Advanced Research Laboratory for the US Navy's Naval Oceanographic Office
- Motors developed for the NASA Space Shuttle program to replace a chemical turbine
- Prototyping efforts to investigate increased continuous torque capacity of the general design using various active cooling schemes are underway

The Lynx/KAT research team has developed several computer models, each progressively more sophisticated, encompassing the electromotive, thermal and control characteristics of the SEMA design. Calibration of these models with prototype test data has been in progress for five years and will continue as additional refinements to the magnetic circuit are explored. Implementation has begun on a thermal model, and it is anticipated that an additional 12 months could be required to achieve a fully reliable model for application design work.

While the general SEMA architecture was developed with commercial industry in mind, almost every potential application thus far evaluated by the Lynx research team has dual use in military applications.

Early application of Lynx T468 servo motor to robotic applications

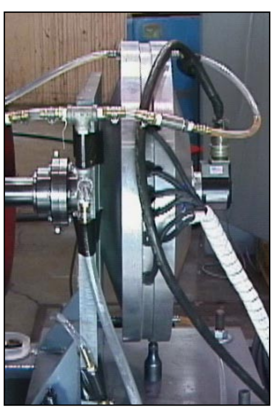
Commercial and Military Potential

The successes of the existing prototype designs are such that it is already viable as the basis of multiple commercial products, with minimal modifications. Interested potential customers have seen demonstrations of the SEMA motors and pursued dialog concerning the modification of the technology for a wide range of applications.

Features of SEMA Technology which recommend it for commercial implementation include:

FutureTruck traction motor

- Higher power density
- Less weight
- Lower volume
- Lower installed cost
- Lower maintenance cost
- Greater reliability
- Less noise
- Greater precision control
- Fewer moving parts
- High fault tolerance
- High efficiency
- Less heat to be rejected



SEMA motor in testing; motor was built as part of a NASA/Boeing research effort

Conclusion

The future of many industrial, military and consumer products dictates that dramatic improvements must be made in motor technology with regard to efficiency, noise, and power density. Incremental improvements in existing motor technologies do not appear capable of delivering system characteristics approaching the specifications required by near-future naval hardware within a promising timeframe. SEMA-based motor technology, however, represents improvements in performance that are dramatic rather than incremental, at costs comparable to conventional technology and can do so with proven, readily available components and manufacturing methods. The implementation of this technology holds tremendous promise for higher performance standards in military and commercial motor systems of all kinds.