Air-core Motors for Haptic Applications

ABSTRACT

ECM's PCB stator air-core motor technology features industry-leading ultra-low-cogging torque. The lack of cogging and torque ripple, among other features unique to ECM technology, is particularly beneficial for haptic feedback applications such as exercise equipment, simulators, and human-machine interaction.

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1 Introduction

A significant source of cogging torque in permanent magnet electric motors comes from the interaction between the permanent magnets in the rotor and the magnetic material in the stator. Designers use several techniques to reduce these effects in motors, such as magnet skewing and slot shaping. These measures reduce but do not eliminate quality of motion issues, which tend to be most evident at the bounds of a motor's operating window. From a system level, torque transformers such as gearboxes, belt drives, and elastic elements may reduce, but not eliminate the effect. When people interact with a motor system these effects can be easily perceived, even at low levels.

ECM's air-core axial flux topology and winding structure tend to provide smooth pole transitions and flux density without the introduction of soft magnetic materials. There is *zero* interaction between rotor permanent magnets and stator magnetic material. Flux density in the gap can be further optimized for quality of motion in the design phase.

This application note describes example applications that ECM has developed to showcase the value of our technology. It also covers techniques that can be used to further improve performance.

2 Effects of Cogging Torque

As the rotor of a traditional motor rotates, the magnetic field from the permanent magnets naturally seeks to align with the paths of least magnetic reluctance, *i.e.*, positions where the magnets line up with the magnetic material in the stator. This creates a repeating magnetic detent effect where the rotor is pulled into preferred positions, or cogging torque. For a constantly rotating motor, this manifests itself as torque ripple that can result in audible vibration and speed instability in precision applications. For a motor driven by a user in haptic applications, cogging torque feels like a notchy or jerky resistance that is most obvious at low speeds or at high torques.

Engineers can employ several techniques to reduce the effect of cogging torque on their applications. At the motor level, magnet skewing and slot shaping can reduce, but not eliminate the cogging torque. At the control level, feedforward compensation and dithering techniques may be used to attempt to smooth out this effect at the cost of increased losses and position measurement and calibration requirements. At the system level, compliance in a belt drive or elastic element can filter out torque ripple, but these types of mechanical systems are susceptible to aging, may require reduced control bandwidth, and have poorer positional accuracy.

ECM technology tackles these problems at the source. Our motors have zero cogging torque and a sinusoidal back-emf that drastically reduces any torque ripple, enabling unmatched performance and a new generation of haptic applications.

3 Examples

ECM has several real-world examples of how our motor technology improves haptic applications.

3.1 Thrustmaster

Figure 1: Internal View of Thrustmaster T598 featuring PCB Stator Technology

For simulated racing environments, the steering wheel provides a direct connection between the user and the simulation both as an input and as a form of user feedback. Cogging torque makes a motor resist rotation in tiny increments, even when unpowered. In a direct-drive racing wheel, that translates into subtle notchiness and audible or tactile vibration in road feel simulation. For competitive sim drivers, those imperfections break immersion and limit precision; the steering wheel is never able to perfectly replicate the real experience.

By eliminating cogging torque, ECM motor technology enables direct-drive racing wheels to recreate a smooth and dynamic driving experience. Every bump, curb, and slip angle is felt exactly as simulated, without disturbance from the motor's internal magnetic structure. Small steering adjustments are frictionless. Furthermore, ECM's highly linear torque to current relationship ensures the virtual car's handling model maps 1:1 to the driver's hands [1].

The T598 was released in October 2024 following a successful prototyping project. Thrustmaster and ECM worked closely together to define the desired specifications and design the optimal solution for the user experience.

3.2 Rowing Machine

Rowing machines, or ergometers, are mechanical systems designed to emulate the dynamics of on-water rowing. They achieve this by converting the user's linear leg and arm movement into rotary motion through a flywheel or equivalent load element. Traditional ergometers use air or fluid resistance mechanisms to emulate the nonlinear drag characteristics of a boat moving through water. Fan-based designs are especially common. Fans provide a cost-effective load that emulates the characteristics of a rowing stroke while maintaining low mechanical complexity.

An electric motor can be used to emulate these same dynamics with high-fidelity. For example, the dynamics of a fan-based ergometer roughly follow a quadratic drag model:

$$J_f \dot{\omega} = \tau_u - \beta_f \omega^2, \tag{1}$$

where ω is the fan speed, J_f is the fan inertia, τ_u is the user input torque, and β_f is the aerodynamic drag coefficient.

In contrast, the dynamics of an electric motor may be modeled as

$$J_m \dot{\omega} = K_t I_{qs} - \beta_m \omega, \tag{2}$$

where ω is the rotor speed, J_m is the rotor inertia, β_m is the rotor drag coefficient, K_t is the motor torque constant, and I_{qs} is the motor torque-producing phase current amplitude.

By commanding the motor's current according to the control law

$$I_{qs} = \frac{1}{K_t}\left(\beta_m \omega - \beta_f \omega^2 + J_m \dot{\omega} - J_f \dot{\omega}\right), \tag{3}$$

and maintaining a sufficiently high-bandwidth current control loop, the motor can precisely reproduce the fan's mechanical response.

Deviations from ideal behavior, such as those introduced by cogging torque or torque ripple, manifest directly as reduced haptic quality. Even minor imperfections contribute to the wrong feel, underscoring the importance of smooth electromagnetic design.

ECM's air-core motor technology is uniquely suited for this application. The absence of magnetic cogging, linearity, and high peak torque capability provide exceptionally smooth torque output allowing the controller to faithfully reproduce resistance profiles.

The motor-controller system is a fully programmable resistance element, emulating fluid drag or even generating variable profiles. Unlike a fan, whose aerodynamic law is fixed, the controlled motor is a reconfigurable dynamic system. The controller is not merely a support circuit, it is an opportunity to define the athlete's physical interaction in firmware. Through firmware alone, one may switch between fan, fluid, or even water-surface emulation models, or dynamically alter the virtual drag to mimic wind, current, or fatigue conditions. This transforms the ergometer from a passive resistance device into an intelligent electromechanical simulator.

ECM's prototype integration demonstrates near-perfect emulation of a fan-based ergometer with dramatically reduced audible noise when compared to existing products. The axial flux form factor further simplifies mechanical integration and minimizes footprint.

Figure 2: ECM's prototype rowing machine integration. The fan was replaced by an ECM stock motor.

Beyond single-user emulation, this framework opens the door to multi-rower synchronization systems. In a real rowing shell, when rowers are out of sync, mechanical and hydrodynamic feedback propagates through the boat as tactile cues. This natural feedback loop fosters synchronization for well-trained rowers.

By linking multiple ergometers, we can approximate this group dynamic by coupling each unit's emulated drag coefficient β_f to the collective stroke behavior:

$$\beta_f\left(\nu_i, \psi_i\right) = K_\nu\left(\nu_i - \bar{\nu}\right) + K_\psi\left(\psi_i - \bar{\psi}\right), \tag{4}$$

where ν_i and ψ_i are the individual rower's stroke rate and phase, respectively, and $\bar{\nu}$ and $\bar{\psi}$ are the group's average stroke rate and phase, respectively.

If a rower strokes too quickly, their drag can increase proportionally, encouraging synchronization. If they lead in phase, the same feedback brings them back into rhythm. This establishes a shared dynamic feedback environment mirroring the cooperative physics of real rowing, which has previously been impossible with static mechanical systems. Furthermore, since the connection between ergometers is purely digital, rowers at distant corners of the world can come together to simulate rowing a boat together.

3.3 Cable Driven Weightlifting Machine

Figure 3: ECM's prototype cable-driven weightlifting machine integration. Weights are simulated via ECM 2 Nm (nominal) shelf stock motors.

A cable machine that "feels" like lifting a physical weight can also be modeled with ECM's technology. Let $\tau_m = K_t I_{qs}$ be the motor torque and r be the effective cable radius.

Neglecting losses for the moment, commanded cable tension is

$$T \approx \frac{\tau_m}{r} \tag{5}$$

With a system rotational inertia of J_s and drag of β_s, the system may be modeled as

$$J_s\dot{\omega} = \tau_m - \beta_s\omega - rT. \tag{6}$$

We may map the linear coordinate, x, via $\dot{x} = r\omega$ such that the system has an equivalent linear inertia of $M_{eq} = \frac{J_s}{r^2}$.

Thus, to emulate a constant weight, W, a simple feedforward current law may be used:

$$I_{qs} = \frac{1}{K_t}\left(rW + \beta_s\omega + J_s\dot{\omega}\right) \tag{7}$$

Over long travel distances, holding T constant is easiest when r is constant. ECM's cable-driven weightlifting machine demo uses a capstan drum system to keep r invariant with payout, so $T = \tau_m/r$ remains constant across the entire stroke.

If a wound spool is used where radius varies with layer such that $r = r(x)$ you can recover constant tension by scheduling motor torque as

$$I_{qs} = \frac{1}{K_t}\left(r(x)W + \beta_s\omega + J_s\dot{\omega}\right) \tag{8}$$

ECM's ironless, air-core machines contribute near-zero cogging and low electrical time constants, the exact properties needed for quiet, high-bandwidth tension control at high force and near zero speed. This yields smoother high-tension holds with no "granular" feel from cogging torque, a higher loop bandwidth for dynamic haptic performance in drops and profiles, and a compact axial-flux form factor that integrates cleanly with a capstan module.

With ECM's motor + software-defined control, "weight" becomes a programmable function delivered with the silence and fidelity that mechanical stacks or competing motor technology cannot match.

3.4 Delta Robot

ECM's delta robot demonstration highlights how our technology enables natural, high-bandwidth haptic interaction through precise force control. In this configuration, three of our shelf-stock servo motors (available for sale) drive the parallel linkages of a delta mechanism, allowing a user to physically manipulate the end-effector while the controller actively compensates for gravity and workspace limits.

Under static conditions, the required joint torques, τ_0, for compensating for gravity's effect on the robot can be found by using Lagrangian analysis.

By computing and then commanding these torques, the end-effector can be translated freely in space with near-zero resistance and apparent weightlessness, limited only by controller bandwidth and friction. ECM's air-core motors make this illusion exceptionally convincing due to their negligible cogging torque, ensuring smooth, transparent back-drive behavior.

To take it a step further and prevent the user from striking the kinematic limits of the robot, a virtual constraint can be imposed in Cartesian space. Define a spherical workspace of radius, r_s, centered at $\vec{x}_0$. A radial penalty force with damping, $\vec{F}_h$, can be used to enforce the boundary as

$$\vec{F}_h = -K_s(\vec{x} - \vec{x}_0) - K_d(\dot{\vec{x}}). \tag{9}$$

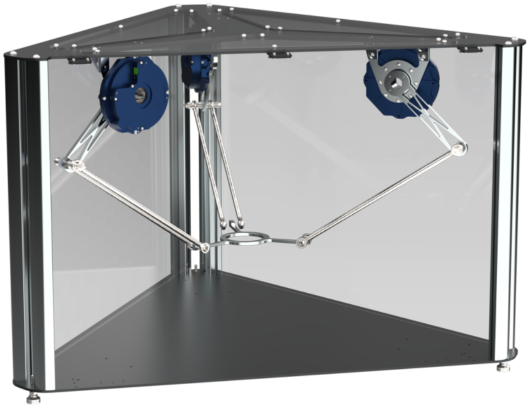

Figure 4: ECM's delta-robot demonstration featuring three ECM 2 Nm (nominal) stock motors working in synchrony.

To transition into the boundary mode without chattering, a simple linear interpolation between the start of the boundary zone, $r_s - \epsilon$, and the sphere radius, r_s, is used where the commanded force, $\vec{F}$, is

$$\vec{F} = \begin{cases} 0 & ||\vec{x}|| < r_s - \epsilon \\ \vec{F}_h & ||\vec{x}|| > r_s \\ \vec{F}_h \frac{||\vec{x}|| - r_s + \epsilon}{\epsilon} & r_s - \epsilon < ||\vec{x}|| < r_s \end{cases} \tag{10}$$

This virtual wall smoothly redirects the user toward the center of the workspace, producing a realistic, spring-like boundary that encourages safe motion without sudden stops.

The success of this demonstration depends on precise, low-latency torque control and lack of magnetic cogging. These two inherent advantages of ECM's air-core design allow the controller to render delicate haptic cues and near-zero-impedance motion, while ECM's compact axial-flux geometry integrates nicely into the overall robot form-factor.

In effect, the delta robot becomes a physical interface for exploring programmable dynamics: one moment it behaves as a weightless object in free space, and the next it can emulate a soft boundary, spring field, or even a complex virtual environment—all defined entirely in software.

4 Conclusion

Traditional actuators impose mechanical signatures, such as cogging, friction, inertia, and delay, that limit how naturally a user can interact with a machine. ECM's PCB stator air-core architecture removes these effects at the source. The motor becomes an ideal torque source and a medium through which software can directly shape perception of force and motion.

Whether reproducing the hydrodynamic load of water, maintaining constant cable tension over long travel, or rendering a virtual gravity field in free space, ECM technology delivers the fidelity needed for true haptic realism. The motor-controller pair is not merely a drive system – it is a programmable interface between human and machine. When torque is smooth, predictable, and precisely controlled, the entire user experience changes.

These demonstrations collectively illustrate a new design space where force, motion, and experience are digitally defined. Applications include training systems, rehabilitation devices, force-feedback controls, and human-interactive robot systems that feel indistinguishable from reality.

References

[1] *Comparing Peak Torque: ECM and a Typical Robot Actuator Motor*. E-Circuit Motors, Inc., 2026.