

# Axial Flux Motors for Reaction Wheel Applications

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## ABSTRACT

Reaction wheel systems provide precise attitude control for satellites, robotics, and stabilization platforms by exchanging angular momentum through an internal flywheel driven by a motor. The action of the motor against this flywheel can transmit torque to the frame in which the motor's stator is mounted.

ECM's axial flux, PCB stator technology offers an integrated solution for reaction wheel applications. The motor rotors themselves are designed to incorporate the necessary moment of inertia. This eliminates coupling mechanisms and bearings, potentially reducing system complexity and overall mass. Using ECM's air-core stator, a reaction wheel built according to this offers low torque ripple and high-bandwidth torque control – with essentially no audible component or vibration. The result is fast, accurate, and smooth torque for precise, stable control in reaction wheel applications.

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## 1 Introduction

Reaction wheel systems are valuable for precise attitude control in satellites, robotics, and stabilization platforms. By accelerating or decelerating an internal flywheel, these systems can generate torques for angular position control or to reject external disturbances, all without control surfaces or external thrusters.

Traditionally, a reaction wheel involves a trade-off. Lightweight motors with low torque capacity decrease system mass, but reduce control authority. Larger conventional motors capable of producing more torque increase mass, but do not necessarily produce an increase in the moment of inertia. An ECM motor can be designed to increase *both* torque capacity and integrated moment of inertia while keeping system mass in check. The only component in the system that increases in mass without contributing to torque capacity and moment is the ECM PCB stator.

An ECM PCB stator comprises copper and fiberglass composite, and has very high specific modulus and strength. Furthermore, since the stator is free of soft magnet materials, it is characterized by high specific (peak) torque capacity and extremely fast electrical time constant. This enables high-bandwidth control and fine torque resolution. A High peak-to-nominal torque ratio supports fast pointing (command following) and stabilization (disturbance rejection). Direct heat rejection via copper features on the stator are ideal for challenging thermal environments.

In this application note, we demonstrate how ECM's axial flux motor technology enables high-performance reaction wheel systems by disclosing the design and performance of a reaction wheel demonstration system built in ECM's lab. In this case, the reaction wheel stabilizes an inverted pendulum, a familiar problem from classical control. The intent is to provide readers the ability to explore their own reaction wheel systems using ECM's technology.

## 2 System Overview



Figure 1: ECM's reaction wheel inverted pendulum.

The reaction wheel inverted pendulum is a classical demonstration of angular momentum exchange and closed-loop stabilization. The system consists of a rigid pendulum arm that can freely rotate about a single pivot axis. At the end of the pendulum, an ECM motor acts against its own rotor (the flywheel), causing a reaction torque that influences the angular position of the pendulum. By carefully controlling motor torque, the system converts the stability type of the upright equilibrium point to stable, including reaching the equilibrium point without saturating the reaction wheel.

The purpose of this demonstrator is twofold:

- to illustrate how inertia can be designed into an ECM axial flux motor to enhance reaction wheel effectiveness, and
- to provide a mathematical framework and practical example for readers who wish to design and implement their own reaction wheel pendulum, spacecraft simulator, or stabilization platform using ECM motors.

## 2.1 Mechanical Configuration

The demonstrator's mechanical structure includes:

- Pendulum arm: A lightweight rigid link mounted on a low-friction bearing to minimize external damping.
- Axial flux reaction wheel: ECM's air-core motor, directly coupled to the pendulum with the stator fixed to the arm and the rotor acting as the reaction mass.
- IMU feedback: Measures the pendulum's angular displacement and rate for closed-loop control.
- Motor controller: An ECM's shelfstock controller capable of precise current control, generating commanded torque with low electrical latency.

A similar motor and controller are available from ECM as a regularly stocked item. Specifications and drawings detailing the ancillary parts are available on request.

Unlike typical reaction wheel systems where a separate flywheel is mounted to the motor shaft, the axial flux motor's rotor serves directly as the momentum storage element. This integration simplifies the mechanical assembly and reduces mass and rotational losses, while naturally increasing the effective moment of inertia of the rotor. For more involved reaction wheel applications, ECM can design motors that trade off mass, inertia, and electrical performance requirements.

The geometry of the system is shown in Figure 2.

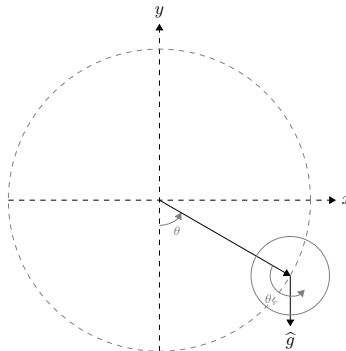


Figure 2: Geometry of the reaction wheel inverted pendulum system.

## 2.2 Electrical and Control Architecture

The controller operates in torque control mode, translating desired torque commands into current references through the motor's known torque constant,  $K_t$ . ECM motor parameters are generally known to an error which is generally a factor of 0.2 (or less) than some servo-type motors. Many parameters are exported with temperature modeling information.

A current controller, implemented in the inverter's firmware, regulates the phase currents via field-oriented control (FOC) to achieve accurate torque response.

A high-level control loop runs on the controller that computes the required reaction wheel torque based on the pendulum's angular deviation from vertical, as measured by the IMU.

These control loops are implemented in the control board integrated with the ECM motor, i.e., they are in the frame of the pendulum.

Thanks to the fast electrical time constant, the current loop operates with minimal lag, enabling stable and responsive torque tracking even under aggressive control gains. The absence of cogging torque ensures that even minute torque changes produce smooth, predictable motion, critical for balancing near the upright equilibrium point.

### 3 Implementation and Mathematical Modeling

The reaction wheel inverted pendulum combines two control problems, switching control laws according to the pendulum's operating regime. The regimes are

1. Swing-up, where the goal is to bring the pendulum from its stable downward equilibrium to the upright position using energy shaping (large signal).
2. Balancing, where the controller maintains stability about the upright position using PID control (small signal linearized).

Both regimes depend on accurate sensing of angular position, rate, and wheel speed, as well as fast torque control in the firmware.

#### 3.1 System Dynamics

The system kinematics can be described by

$$J\ddot{\theta} + mgl \sin \theta = K_t i_q - \beta \dot{\theta}_r \quad (1)$$

$$J_r \ddot{\theta}_r = K_t i_q - \beta \dot{\theta}_r \quad (2)$$

where  $\theta$  is the pendulum's angular position measured from the downward vertical,  $m$  is the pendulum's mass in kg,  $l$  is the distance from pivot to pendulum's center of mass in m,  $J$  is the pendulum's moment of inertia about the pivot in  $\text{kg m}^2$ ,  $i_q$  is the motor's q-axis current in A,  $\theta_r$  is the rotor angle in rad,  $J_r$  is the rotor's inertia in  $\text{kg m}^2$ ,  $\beta$  is the rotor drag constant in  $\text{N m s}$ , and  $K_t$  is motor torque constant in  $\text{N m A}^{-1}$ .

The first equation describes the pendulum dynamics influenced by the wheel's reaction torque, and the second represents wheel acceleration as a function of applied motor torque and motor drag.

#### 3.2 Swing-Up Control

The swing-up phase requires increasing the pendulum's energy until it can transition into the balancing region. A common and effective approach is energy-based control, where the desired motor torque is derived from the difference between the current and target total energy.

The current pendulum energy, neglecting the energy stored in the rotor, is

$$E = \frac{1}{2} J \dot{\theta}^2 + mgl(1 - \cos \theta). \quad (3)$$

We may form a control law,  $u$ , as

$$u = K_e \dot{\theta} (E_d - E) - K_\omega \dot{\theta}_r, \quad (4)$$

where  $E_d$  is the desired system energy, *i.e.*,  $2mgl$ .

This control law naturally pumps energy into the system in phase with the pendulum's motion, causing the amplitude of oscillation to grow until it approaches the upright equilibrium, at which point control transitions to the balancing mode.

Note that this control rule has a damping term that penalizes the rotor speed,  $\dot{\theta}_r$ , so that

- The rotor speed remains centered around zero
- The pendulum arrives at the top with minimal stored energy in the rotor

### 3.3 Balancing Control

Once near the vertical position ( $\theta \approx \pi$ ), the system can be linearized:

$$J\ddot{\theta} - mgl\theta = K_t i_q - \beta \dot{\theta}_r \quad (5)$$

A control law of the form

$$u = -K_p(\theta - \theta_0) - K_{d,p}\dot{\theta} + K_{d,r}\dot{\theta}_r + K_\theta\theta_r, \quad (6)$$

is typically sufficient for stabilization. This control regulates both pendulum and wheel angles and velocities to ensure that any bias in the angle measurement is taken into account [1].

## 4 Reaction Wheel Performance

A video showing the reaction wheel inverted pendulum in operation can be found online at <https://www.youtube.com/shorts/d0WGef9nN04>.

## 5 Conclusion

This note and accompanying video show some of the possibilities of reaction wheel applications using ECM PCB stator technology. In particular, ECM's axial flux format and design-by-optimization allow systems that optimize moment of inertia, torque, and may reduce overall system mass. ECM's motor dynamics allow control loops to operate quickly and smoothly.

Additional features of the technology that are valuable to this application include

- high specific stiffness and strength of stator
- high thermal conductivity to periphery of stator
- tight control of machine parameters
- ability to define optimality criteria for design
- scaling of moment with torque capacity

- exceptional peak to nominal torque rating
- no loss of linearity through peak torque
- exceptional quality of motion

As each ECM design is different, the numerical advantage in each case will be slightly different.

The mathematical framework presented here—covering system dynamics, energy-based swing-up control, and linearized balancing control—provides a foundation for implementing reaction wheel systems in applications ranging from satellite attitude control to robotics. The low audible noise and mechanical vibration further make ECM motors well-suited for sensitive instrumentation, optics, and laboratory environments where quiet operation is essential.

For additional technical specifications, custom motor configurations, or assistance with your reaction wheel application, please contact ECM via <https://www.pcbstator.com>.

## References

- [1] Daniel J. Block, Karl J. Åström, and Mark W. Spong. *The Reaction Wheel Pendulum*. Springer Cham, 1st edition, 2022.