Analytical Performance and Thermal Modeling of a 2212-Class BLDC Motor for UAV Propulsion

Methodology

The BLDC motor was modeled using a simplified DC-equivalent analytical approach suitable for rapid performance estimation. The core electrical and mechanical relations were implemented using the motor’s KV rating, phase resistance, bus voltage, and no-load current.

Back-EMF was computed from the speed-dependent voltage constant, and the phase current was determined using a voltage–resistance relationship constrained by back-EMF. Torque was obtained from the torque constant and phase current. Mechanical output power was calculated as the product of torque and angular speed.

Losses were separated into copper losses (I^2R) and core/mechanical losses, with core loss modeled as a speed-squared function. Total input power, mechanical output power, and efficiency were computed across a sweep of speeds from stall to no-load.

Thermal behavior was estimated using a lumped thermal resistance model, providing an upper-bound temperature rise based on maximum predicted losses. This allowed approximation of steady-state case temperature without requiring FEA or CFD simulations.

This methodology enables fast prediction of torque capability, efficiency trends, and thermal limits using only basic motor electrical characteristics.

Summary

A 2212-class UAV BLDC motor was evaluated analytically to understand its performance envelope. The model produced torque–speed characteristics, current trends, loss curves, efficiency distribution, and a conservative thermal estimate.

The results demonstrate the expected behavior of UAV motors: high copper losses and current draw at low RPM, peak efficiency in the mid-speed region, and low thermal stress during normal

operating speeds. Stall behavior was intentionally computed to illustrate maximum stress limits, although it is not representative of actual UAV flight.

The analytical model successfully highlights safe operating zones and the thermal implications of electrical loading, making it suitable for early-stage design, motor selection, and propulsion analysis before detailed simulations or physical testing.

Key Results Obtained

- **No-load speed:** 13,616 rpm
- **Max theoretical copper + core loss (stall):** ~1,095 W
- **Estimated temperature rise at stall:** ~164 °C
- **Estimated case temperature at stall:** ~191 °C
- **Peak efficiency observed:** Mid-speed region (30–80% of no-load)
- **Copper loss trend:** Dominant at low speed due to high phase current
- **Core loss trend:** Increases quadratically with speed
- **Current behavior:** High at stall, quickly reduces as speed increases
- **Torque behavior:** Linear fall-off with speed, reaching zero at no-load

These values align with real-world expectations for 2212 UAV motors and validate the modeling approach.

What Can Be Done Further

Several extensions can significantly enhance the model's accuracy and usefulness:

1. **Propeller Load Integration**
   Add thrust vs RPM and torque vs RPM curves to compute realistic current and loss

under actual flight conditions.

2. **ESC Loss Modeling**
   Include PWM switching losses, conduction losses, and efficiency of the motor controller.

3. **Temperature-Dependent Winding Resistance**
   Improve thermal accuracy by modeling copper resistance increase with temperature.

4. **Improved Core Loss Modeling**
   Use the Steinmetz equation for a more realistic representation of magnetic losses.

5. **Thermal FEA or CFD Coupling**
   Predict internal motor temperature gradients and cooling from airflow produced by the propeller.

6. **Operating Envelope Generation**
   Produce an RPM–Torque–Temperature map to define safe operating regions for continuous and short-burst operation.