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Parametric Propeller Design & Low Reynolds Number Performance Benchmarking

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1) Summary / Purpose

Design a parametric propeller family (150–250 mm diameter) and evaluate aerodynamic performance at low Reynolds numbers relevant to micro-UAVs. Build a reusable modeling + analysis pipeline that RES can extend for future research tracks and client work.

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2) Objectives

- O1 – Generator: Build a parameterized CAD model that varies diameter, pitch, chord distribution, twist, camber, blade count (2–4) and hub geometry.
- O2 – Variants: Produce ≥ 3 distinct propeller variants covering a practical design space (e.g., low-pitch efficiency, balanced general use, high-thrust).
- O3 – Analysis: Generate section polars (lift/drag vs α, Re) and perform Blade Element/Momentum Theory (BEMT) to estimate thrust, torque, and η (efficiency) across RPM and advance ratios.
- O4 – Evidence: Deliver an 8–10 page technical brief with methods, assumptions, charts (T-RPM, η-J), and design recommendations.
- O5 – Handoff: Release clean source files + drawing set and a structured spreadsheet/Python workbook so Juniors can extend the study.

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3) Scope of Work

3.1 CAD (Parametric Generator)

- Select baseline airfoil families suitable for low Re (e.g., thin cambered sections).
- Define parameter set: D, P/D, radial chord law, radial twist law, thickness/camber, # of blades, hub/fillet.

- Implement features: blade lofts, hub with standard shaft bore, configurable fillets, export templates.
- Create configuration table (CSV/JSON) that maps parameter sets → named variants.

3.2 Aerodynamics (Low-Re)

- For each section Re range, produce polars (Cl, Cd vs α).
    - Use XFOIL (or OpenVSP's VSPAERO for cross-checks) to derive polars at representative Re along the span.
- Implement BEMT with tip-loss factor; integrate along blade span for thrust/torque at RPM sweep.
- Compute $\eta = (T \cdot V) / (Q \cdot \omega)$ and advance ratio $J = V / (n \cdot D)$; generate performance maps.

3.3 Packaging & Communication

- Drawings: Hub interface, blade root, key dimensions & tolerances (PDFs).
- Data Book: Polars, assumptions, BEMT equations, units, constants.
- Report: Methods, validation sanity checks, results, limitations, next steps.
- Repository: Organized folders with versioned CAD, scripts, outputs.

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4) Deliverables

1. Parametric CAD: Native files + step/iges export; 3+ named variants.
2. Drawing Set (PDF): Hub/assembly + at least one blade section drawing with critical dims.
3. Analysis Workbook: Spreadsheet or Python notebook implementing BEMT with inputs/plots.
4. Technical Brief (8–10 pages, PDF): Motivation, method, results, trade-offs, recommendations.

5. Release Notes: Readme with how to re-run, parameter table, version info.

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5) Tools & Stack

- CAD: Fusion 36
- Aero: XFOIL
- Computation: Python

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6) Assumptions & Constraints

- Low-Re operation typical of 150–250 mm props and small drones.
- Steady, incompressible flow; no CFD in v1 (analytic + semi-empirical only).
- Manufacturing optional; 3D printed demo allowed for geometry visualization.
- No proprietary airfoil data; open-source or public polars only.

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7) Out of Scope (v1)

- Experimental validation (thrust stand) and full acoustic analysis.
- Composite layup or advanced manufacturing process dev.
- Full mission optimization (vehicle-level sizing).

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8) Milestones & Timeline (example)

- M0 (Day 0–3): Requirements + baseline airfoil shortlist + repo scaffold.
- M1 (Week 1): Parametric CAD generator complete; variant A baseline exported.
- M2 (Week 2): XFOIL polar set generated for spanwise Re grid; data sanity-checked.
- M3 (Week 3): BEMT implementation and plots for A/B/C variants (T, Q, η vs RPM/J).
- M4 (Week 4): Drawings (hub + key dims), write report, design recommendations.

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9) Quality Standards

- CAD: Fully constrained sketches; named parameters; no red-dimension warnings.
- Drawings: Title block, units, tolerances, rev control, legible section views.
- Analysis: Units tracked; equations referenced; plots labeled with axis units; sensitivity table (e.g., ±5% in Cl/Cd).
- Reproducibility: A new user can run the analysis from Readme without guessing.

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10) Risks & Mitigations

- Unstable XFOIL polars at very low Re: smooth with limited α range; use multiple Re points; cross-check with literature-based profiles.
- Overfitting to a single flight speed/RPM: evaluate across a sweep; present operating envelope not single point.
- CAD parameter interactions (self-intersections): guardrails in parameter ranges; test extremes early.
- Time creep: lock scope to 3 variants; defer CFD/physical tests to v2.

11) Success Criteria / KPIs

- Parametric model produces 3+ valid variants without geometry failures.
- BEMT tool runs end-to-end and outputs T-RPM, Q-RPM, η-J plots for each variant.
- Report demonstrates clear trade-offs (e.g., high-pitch vs low-pitch) with justified recommendations.
- Repository passes internal handoff check (another engineer can reproduce results).