Aircraft Design Principles for RC Aircraft Competitions

A Conceptual Summary mostly based on "General Aviation Aircraft Design" by G. Gudmundsson

Aaryan Lath

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Note to the Reader

This document summarizes fundamental aircraft design concepts from "General Aviation Aircraft Design" by Egill Thor Gudmundsson (Elsevier, 2022), and "Aircraft Design: A Conceptual Approach" by Daniel P. Raymer and has been tailored for RC aircraft projects (other resources such as class notes used are mentioned at the beginning of every section/subsection). While principles from full-scale design are relevant, this summary is not exhaustive, and there have been RC specific adaptations. Use this for conceptual understanding and to stimulate further critical thinking for your specific design challenge. Always prioritize current competition rules as the primary regulatory document.

Contents

1 The Aircraft Design Process

Airplane design can seem daunting due to the many demands placed on an aircraft. A systematic design process is necessary because it provides an organized way to tackle these challenges. For new aircraft, most are designed to fulfill a specific role or mission. For the competition, the "mission" is defined by the competition rules (e.g., maximizing payload, taking off within a set distance). The "constraints" include these rules, your budget, available materials, and manufacturing time. A design process will help the team by:

- Systematically addressing all rule requirements.
- Managing the project efficiently from concept to flight.
- Optimizing the aircraft's performance for the specific scoring formula.
- Identifying potential problems (e.g., structural weakness, instability) before you build or fly, saving time and resources.
- Making informed trade-offs, for example, between a very lightweight structure (potentially fragile) and a more robust one (heavier, reducing payload).

Essentially, a good process helps ensure that the team develops the best possible aircraft to meet the competition's objectives.

1.1 Aircraft Design & Development Process

The aircraft design process typically starts with requirements and ends with a certified product.

An elementary view of the design process includes these phases in order: Requirements, Conceptual Design, Preliminary Design, Detail Design, and Fabrication. However, in reality, these phases often overlap significantly to use resources more effectively. Key milestones in a more detailed industrial process include:

- **Configuration Freeze**: A date after which no major changes to the aircraft's external shape (Outer Mold Line - OML) are allowed. This allows detailed structural and systems design to proceed.
- **Go-Ahead Approval**: Management's decision to fund and proceed with the prototype development.

The process often involves iterations, especially if the design is unconventional or if issues arise that require modifying the OML.

RC Aircraft Context: Our team will follow a similar, albeit compressed, workflow. (Refer to SAE Aero Design 2026: Strategic Engineering and Project Plan)

Iteration is key since we will not be making a flawless aircraft from the beginning; Thus, test results often lead back to design modifications.

1.2 Fundamental Phases of Aircraft Design

The design process is typically broken down into several key phases:

1.2.1 Requirements Phase

This is where the mission, capabilities, and regulatory constraints are defined. It's essentially a "wish list" of what the aircraft must achieve (e.g., range, speed, payload). *Remembers AAE 251 and finally understands the importance of paying attention in class*

RC Aircraft Context: Our requirements come directly from the competition rules: takeoff distance, landing requirements, payload capacity, dimensional constraints, material restrictions, safety rules, and scoring formula. Understanding these thoroughly is Step 1. Thus, from the rules and design guides, we might perform sensitivity studies, use a Pugh matrix, etc. This phase can overlap with the Conceptual Design Phase.

1.2.2 Conceptual Design Phase

This phase involves initial sizing, estimation of cost, performance, stability, and evaluating compliance to the rules. It provides an assessment of performance, aesthetics, and the scope of development. Characteristics defined include:

- Type of aircraft.
- Special aerodynamic features (e.g., flaps/slats, etc.).
- Adhering to the competition rules and missions.
- Technology (materials, controls), manufacturing ease, maintainability, costs.

RC Aircraft Context:

- **Configuration**: High-wing monoplane is very common for stability and ease of payload integration. Pusher vs. tractor propeller. Tail design (conventional, T-tail, V-tail, twin boom).
- **Aerodynamic Features**: Flaps are essential for maximizing lift at low speeds. Slats or leading-edge cuffs might be considered. Wing aspect ratio and planform shape choices. (We mostly use XFLR5 for this analysis).
- **Technology**: Choice of construction materials (balsa, foam, composites), motor-battery-propeller combination, type of servos.
- **Manufacturing Ease**: How easy will it be for the team to build with available resources and skills? (never overestimate your skill)
- **Maintainability**: Can it be quickly repaired at the competition in case of something breaking?

The deliverables for these are the decision matrices and then a potential Preliminary Design Review where we defend our choices (the PDR going to be after the Preliminary Design Phase).

1.2.3 Preliminary Design Phase

This phase involves more detailed design work, often on a Proof-of-Concept (POC) or prototype. It confirms viability, exposes problems, and allows evaluation of solutions. Tasks include detailed geometry development, layout of major load paths, detailed weight estimation, performance evaluation, and stability analysis.
RC Aircraft Context:

- Detailed CAD model of the entire aircraft. (This is more robust in the detail design phase.)

- Selection of specific airfoils.
- Refined aerodynamic analysis (e.g., XFLR5, simple CFD).
- Structural analysis of critical components (wing spar, landing gear, fuselage payload bay).
- Detailed weight and balance calculations, ensuring CG is within acceptable range with and without payload.

The deliverable is a drawing package and a report to decide on building the POC (our competition aircraft).

1.2.4 Detail Design Phase

This phase involves the detail design of the airframe and system integration for the prototype or production aircraft. It includes structural details, mechanical design, avionics, tooling design, etc.

RC Aircraft Context:

- Creating detailed drawings/CAD files for every part to be manufactured (ribs, spars, fuselage formers, control horns, payload mechanism parts).
- Planning the manufacturing process (jigs, fixtures, cutting templates).
- Layout of all electronics (receiver, servos, Electronic Speed Controller (ESC), battery) and wiring.
- Design of payload retention and release mechanisms.

1.2.5 Proof-of-Concept (POC) Aircraft and Testing

Construction of the POC begins during detail design . This is followed by various tests (wind tunnel, structural, systems, etc.) to progress to our maiden flight.

RC Aircraft Context: This is the actual building of our competition aircraft.

- **Structural Tests**: Wing load testing (to a factor of safety defined by rules or good practice), landing gear drop tests (if concerned).
- **Systems Tests**: Ensuring payload mechanism works, controls move correctly and in the right direction, motor runs smoothly.
- **Ground Tests**: Range check, CG check, control surface deflection measurements.

1.2.6 Development Program Phase

This follows a successful preliminary design and often begins before the maiden flight. It involves flight test engineers and pilots to establish operating limitations, pilot's operating handbook (**POH**), and emergency procedures. The goal is a certifiable aircraft.

RC Aircraft Context:

- **Flight Testing Program**: Systematically testing the aircraft's flight envelope, stall characteristics, takeoff performance with increasing payload.
- **Establishing "POH"**: Notes for your pilot on best climb speeds, stall speeds, flap settings for takeoff/landing, and any flight quirks.

- **Emergency Procedures**: What to do if the motor cuts out, control linkage fails (though this usually means a crash for RC). Mostly, it's about safe flight operations.
- **Maiden Flight & Flight Testing**: The most critical step. Verifying stability, control, performance, and identifying any issues. (The plane will most likely crash during the maiden flight so don't be dis-heartened if it does, just keep enough of a wiggle room to iterate.)
- Goal: An aircraft that reliably performs the mission.

1.2.7 Post-Development Programs

RC Aircraft Context: Learning from one competition (what worked, what didn't, what other teams did) to improve the design for the next year's competition. We learnt a lot from the 2025 competition so do refer to the feedback document.

Figure 1: Aircraft design process for a typical GA aircraft. (Source: Gudmundsson, Ch 1, Fig. 1-3)

1.3 Key Concepts in the Aircraft Design Process

1.3.1 Definition of the Mission

RC Aircraft Context: Your mission, *should you choose to accept*, is primarily to maximize the score according to the current year's rules. This usually involves lifting the maximum possible payload while meeting takeoff/landing distance constraints, size limits, and potentially other specific tasks. For instance, if the rules heavily penalize long takeoff rolls, the design must prioritize short takeoff performance, perhaps even at the expense of some payload.

1.3.2 Performance Requirements and Sensitivity

Specific performance targets like takeoff distance, climb rate, and range must be defined. It's also vital to understand performance sensitivity – how performance changes with off-design conditions.

RC Aircraft Context:

- **Key Performance Targets**: Takeoff within X feet, stall speed below a safe limit for landing, ability to climb with payload.
- **Sensitivity**: How does an increase in payload affect takeoff distance and stall speed? How does battery voltage drop affect thrust? Understanding these helps in making strategic decisions during the competition (e.g., how much payload to attempt). Note that doing a sensitivity analysis makes the most sense when there are multiple different types of conflicting missions involved such as in DBF, in SAE Aero we might not necessarily need to do it. Refer to this video for understanding more about sensitivity analysis.

1.3.3 Handling Requirements (Stability and Control)

RC Aircraft Context: Good handling is critical. The aircraft, especially when heavily loaded, needs to be stable and controllable for the RC pilot.

- **Stability**: The aircraft should have positive static and dynamic stability to be flyable, especially at low speeds and high angles of attack typical of takeoff and landing with heavy loads.
- **Control Authority**: Sufficient elevator, rudder, and aileron effectiveness to control the aircraft throughout its flight envelope.
- **Flap Effects**: Deploying flaps will increase lift but also pitching moment. The design must account for this so the pilot can maintain control. (The trim condition)
- Many teams use flight stabilization systems (gyros) to aid the pilot, but fundamentally good aerodynamic design is preferred. (check the competition rule book for further clarifications on such systems.)

1.3.4 Ease of Manufacturing

This profoundly impacts engineering and cost. A straight, constant-chord wing is cheaper to build than a tapered one but less aerodynamically efficient.

RC Aircraft Context:

- **Simplicity is Key**: Designs that are easy to build accurately with available tools (laser cutter, 3D printer, hand tools) and skills are more likely to be successful.
- **Wing Planforms and Manufacturability**: Discussed further in Section 4.2
- **Fuselage Construction**: Slab-sided fuselages are easiest. Round or complex curved fuselages reduce drag but are harder to build using traditional materials.

1.3.5 Certifiability

RC Aircraft Context:

- **Performance-Based Nature**: Many SAE rules are performance-based (e.g., "the aircraft must take off within 100 feet").
- **Technical Inspection as "Certification"**: The pre-competition technical inspection by judges serves as a form of "certification", verify that the aircraft conforms to the rules.

Need to pass the technical inspection at the competition, which verifies compliance with all rules (dimensions, weight, safety features like arming plugs, payload retention). A design that cannot pass inspection will not fly or score. CDRs and something else which is extremely important is approaching faculty advisors such as Tom to get feedback.

1.3.6 Features and Upgradability (Growth)

Aircraft weight tends to increase over time due to added capabilities or systems. It's wise to design for a weight 5-10% higher than initially projected.

RC Aircraft Context: While you aim for the lightest structure to maximize payload, designing with some margin can be beneficial. For example, if your structure is slightly overbuilt, it might handle unexpected hard landings better. Having some robustness and perhaps slight oversizing of components is important.

1.3.7 Maintainability and Accessibility

RC Aircraft Context: This is extremely important for a competition environment.

- **Field Repairs**: Your aircraft might get damaged during testing or even at the competition. Designs that allow for quick repairs (e.g., easily replaceable landing gear, accessible control linkages, simple wing attachment) are advantageous.
- **Accessibility**: Easy access to the battery (for quick changes), receiver, ESC, servos, and the payload mechanism might be important. You don't want to disassemble half the plane to change a battery or adjust a servo.
- Consider using fasteners (screws, bolts) over glue for some components that might need removal or replacement.

1.3.8 Lean Engineering and Lean Manufacturing

RC Aircraft Context: The only reason for caring about this is to keep costs low.

- **Build Time**: Avoid overly complex parts if simpler ones work since it adds time to build the aircraft in the already short time frame, delaying testing which is absolutely necessary for a good final design.
- **Minimize Weight**: This is the ultimate "lean" goal for payload aircraft. Every gram saved in structure is a gram available for payload.
- **Material Efficiency**: Plan cutting of balsa sheets, foam blocks, or composite cloth to minimize waste.

1.3.9 Integrated Product Teams (IPTs)

Effective communication and coordination between these "sub-teams" are vital for a successful integrated design.

1.4 How to Design a New Aircraft

1.4.1 Conceptual Design Algorithm

Table 1-4 in the source text provides a detailed step-by-step algorithm. Here's an adaptation for RC aircraft:

Step 1: Understand Requirements: Thoroughly study the current rules (mission, constraints, scoring).

Step 2: Budget & Resource Assessment: Estimate build costs. Not for "break-even", but to stay within team budget.

Step 3: Constraint Diagram: Plot key performance constraints based on rules (e.g., takeoff distance vs. weight, stall speed limits vs. wing loading, payload vs. aircraft weight). This helps identify a feasible design space.

Step 4: Select Critical Design Parameters: From the constraint diagram, choose initial targets for wing loading (W/S) and thrust-to-weight ratio (T/W) (or power loading for electrics).

Step 5: Initial Weight Estimation: Make a rough estimate of empty weight and maximum takeoff weight (MTOW) using historical data from previous team aircraft or similar RC planes. Payload will be MTOW minus empty weight and battery.

Step 6: Initial Wing Area Thrust/Power: Using target W/S and estimated MTOW, calculate initial wing area (S_w). Estimate required thrust/power. This requires an estimate for maximum lift coefficient ($C_{L_{max}}$), considering airfoil and flap choices. Ensure stall speed requirements are met.

Step 7: Initial Tail Surface Sizing: Use tail volume coefficients (V_h, V_v) to get initial estimates for horizontal and vertical tail areas and tail moment arms.

Step 8: Wing Layout Proposal: Define initial wing aspect ratio (AR), taper ratio (TR), airfoil(s), planform shape, dihedral, and washout. (Refer back to Section 1.2.3 (4) discussion on RC wing planforms).

Step 9: Comparative Study & Initial Configuration: Research past successful designs and relevant RC planes. Decide on a basic configuration (e.g., high wing, conventional tail, pusher/tractor) and propulsion (electric motor, propeller size estimate). Conduct trade studies for those. *Refer to the Engineering Plan document for greater clarity on examples of trades*

Step 10: Sketch Candidate Configurations: Create more detailed sketches or simple 3D models of a few promising configurations. Evaluate pros and cons, then select one candidate for further development.

Step 11: Propulsion System Selection: Based on thrust/power needs, select a specific motor, ESC, battery, and propeller combination. Consider static thrust and efficiency.

Step 12: Stability & Control Analysis: Perform static stability analysis (longitudinal and lateral-directional). Check for positive static margins. Use tools like XFLR5 or OpenVSP. Dynamic stability is harder to analyze without advanced tools but good static stability usually leads to acceptable dynamic behavior for RC.

Step 13: Refine Tail Geometry: Adjust tail surface areas and moment arms based on stability analysis to achieve desired stability margins and control authority.

Step 14: Layout Design Modifications:

- **Structural Load Paths**: Identify primary load paths (wing spars carry bending, fuselage carries payload loads, landing gear absorbs landing impact). Design structure accordingly.
- **Control System Layout**: Plan servo locations, pushrod/cable runs, control horn geometry. Ensure minimal slop and good geometry.
- **High-Lift Systems**: Design flaps (type, size, deflection) and their actuation mechanism.
- **Landing Gear Layout**: Design a robust landing gear (tricycle or taildragger) capable of handling rough fields and heavy loads.

Step 15: Detailed Mass Properties Breakdown and establishing CG: Create a detailed component-by-component weight estimate for the candidate configuration (structure, propulsion, electronics, payload mechanism). Calculate the empty weight CG. Develop a CG loading diagram showing how the CG shifts with payload and battery placement. Determine allowable CG range for stability.

Step 16: Establish CG Envelope: Define the forward and aft CG limits the aircraft can tolerate while remaining stable and controllable.

Step 17: Fuselage Layout: Design the fuselage, paying close attention to payload bay dimensions and accessibility, electronics placement, wing and tail mounting points, and landing gear integration.

Step 18: Stall Characteristics: Design for benign stall behavior. Test this in the wind tunnel or during flight!

Step 19: Drag Minimization: Perform a drag buildup estimation (parasite drag of components + induced drag). Identify areas to reduce drag (e.g., smooth surfaces, faired landing gear if feasible, minimize gaps).

Step 20: Performance Re-evaluation: Re-calculate takeoff distance, climb performance, and stall speeds with the refined design and weight estimates. Create a payload vs. score chart based on the rules.

Step 21: Optimize and Refine: Iterate on the design. Are there areas to save weight, improve lift, reduce drag, or simplify manufacturing?

Step 22: Rule Compliance Check: Systematically verify that every aspect of the design complies with all competition rules. This is your "regulatory evaluation."

Step 23: Freeze OML (Finalize CAD): Once satisfied, finalize the 3D CAD model and detailed drawings. This is your "frozen configuration".

Step 24: Detailed Load Analysis: For critical parts like the wing spar, tail booms and connection points, perform a more detailed load analysis based on expected flight loads and rule-defined load factors (if any) .

Step 25: Move to Preliminary Design of POC (Build Phase): Transition from paper/CAD design to actually building your aircraft.

This process is iterative. Discoveries in later steps often require revisiting earlier steps. The step to re-iterate from often depends on the changes that are being made, however, the lowest step to iterate from is Step 6 when there are changes made to the wing.

Figure 2: Typical tasks for designing a new aircraft. (Source: Gudmundsson, Ch 1, Fig. 1-12)

1.4.2 Implementation of the Design Algorithm

Spreadsheet software (like Microsoft Excel or Google Sheets) is ideal for implementing many parts of this design algorithm.

- Organize calculations in different worksheets (e.g., weight, aerodynamics, performance, stability).
- Have a "General" tab for key parameters (e.g., wingspan, MTOW, air density) that are used in multiple worksheets to ensure consistency when changes are made.
- Use formulas rather than hardcoded numbers wherever possible to facilitate iteration.

RC Aircraft Context: I cannot emphasise enough how important documentation is. A reason why aircrafts crash is due to the lack of transparency and which stem from many reason, one of them being the lack of documentation and knowing what changes are being made to the aircraft. Spreadsheets are invaluable for teams such as ours to quickly perform trade studies (e.g., how does changing aspect ratio affect wing weight and induced drag?), track weight, and calculate performance. Consistent models shared among team members is a must.

1.5 Elements of Project Engineering

Have a Project Plan, proper task management, make the Gantt Diagrams, and having proper documentation is the main crux of this section.

- **CAD Files**: Establish a clear naming convention and version control system for CAD parts and assemblies.
- **Design Reports/Calculations**: Standardize format for reports. Keep organized design notebooks or digital folders for calculations, analyses, and decisions. This is invaluable for writing the final design report.
- **Manufacturing Drawings**: If creating 2D drawings from CAD, use a consistent system.

1.6 Presenting the Design Project

Effectively communicating your design is important, since some competitions such as the SAE Aero Design does have a presentation round.

1.6.1 Three-View Drawings

Fundamental presentation tool showing top, side, and frontal views of the aircraft. Essential for any design proposal package. A standard requirement for your design report. Should be clear, dimensioned, and accurately represent your aircraft.

1.6.2 Images Using Finite Element Modelers (FEA)

FEA software can produce compelling images of stress distributions and load paths. Use with care, as results may not always perfectly match reality.

RC Aircraft Context: Include clear images of the setup, boundary conditions, and results (stress plots, deformation plots) in your report to justify design choices.

1.6.3 Images Using Computational Fluid Dynamics (CFD) Software

CFD is used to predict and investigate airflow around bodies. CFD images (pressure plots, streamlines) can be very sophisticated but should also be interpreted with caution regarding their accuracy.

RC Aircraft Context: Include informative plots in your report. Clearly state assumptions and software used.

1.6.4 Cutaway Drawings

Excellent for illustrating the internal complexity of an aircraft (structure, systems, payload integration).

RC Aircraft Context: A detailed cutaway view in the design report can be very effective for showing judges how your internal structure is laid out, how the payload mechanism works, and where electronics are placed.

1.6.5 Engineering Reports

RC Aircraft Context: There are points for the technical reports as well. Refer to the Drive to see a couple of really good technical reports from past competitions.

This concludes the summary of Chapter 1 with an emphasis on the high-level design process for the competition. Remember that this is a starting point, and continuously learning is key to success.

2 Aircraft Cost Considerations

While detailed cost analysis models for General Aviation aircraft, like those discussed in the source text, involve complexities such as labor rates, certification, and market projections, the core principle of understanding and managing costs is vital for any project. For our team, this isn't about profit margins but about maximizing performance and being within the budget we have for the year.

2.1 Budget-Conscious Design and Part Selection

Making smart choices about where to allocate the limited funds.

2.1.1 Mindful Spending and Tracking

The first step is to **create a somewhat detailed budget** at the beginning of the project and diligently **track all expenses** (This is the job of the treasurer and leads who will let the team know when going overboard. This includes everything from raw materials to components and even small items like glue, screws. Maintaining a Bill of Materials (BOM) with updated costs is essential.

2.1.2 Strategic Part Selection and Trade-offs

Every component choice has cost implications, often tied to performance or weight.

- **Propulsion System (Motor, ESC, Battery, Propeller)**:
  - A cheaper, less powerful motor might save initial cost but could necessitate a significantly lighter and potentially more fragile airframe to achieve takeoff. It might also limit your maximum payload capacity, directly affecting score. (There is also a limit imposed by SAE so this shouldn't be too bad)
  - High-performance batteries (e.g., higher C-rating for better current delivery, or higher capacity for more flight attempts/testing) usually cost more. We need to balance performance needs with budget.
- **Servos**:
  - Metal-gear servos are generally more durable and precise than plastic-gear servos but cost more. (e.g., a small rudder on a predominantly aileron-controlled plane can have a plastic one however, it again depends on our preliminary design).
- **Materials**:
  - The cost of 3D printing filament versus the time and skill to handcraft a component from balsa/ply is a potential trade-off.

2.1.3 Compromising on Non-Critical Aspects

To save money for critical components, consider where compromises can be made:

- **Excessive Redundancy**: While some spare parts are essential (props, batteries), overstocking every component can strain the budget. Prioritize spares for items most likely to break or wear out.

2.1.4 Identifying Critical Components: Where Not to Skimp

Certain components are fundamental to the aircraft's success and safety. Attempting to save too much money here can be counterproductive

3 Initial Sizing (Chapter 3)

Initial sizing is a foundational phase in aircraft design where we determine the aircraft's basic characteristics, such as its overall weight, the amount of "fuel" (or battery for electric aircraft) it needs, the size of its wing, and the required power from its engine or motor. This process impacts all subsequent design choices, performance capabilities, and even manufacturing complexity. The goal is to find a balanced design that meets all specified mission requirements, which for us, the ceilings or floors are dictated by the competition rules, but we still need to find an optimal design.

3.1 The Iterative Nature of Sizing

Aircraft sizing is inherently iterative. This means we often have to make initial guesses for some parameters and then refine them through calculations. For example, the total weight of the aircraft depends on the weight of its structure, engine, and battery. However, the required battery weight depends on the mission and the aircraft's efficiency, which in turn is affected by its total weight. This chapter will follow the logical design sequence: first, we use a constraint analysis to determine the required performance characteristics, then we use those characteristics to estimate the takeoff weight, and finally, we translate those values into a physical geometry.

3.2 Phase 1: Constraint Analysis

Before we can estimate the aircraft's weight, we must first understand the performance it needs to achieve. Constraint analysis is a powerful method that translates mission requirements (e.g., takeoff distance, climb rate, top speed) into the required design parameters of **wing loading (W/S)** and **thrust-to-weight ratio (T/W)**.

3.2.1 Some Examples of Design Parameters for Constraint Analysis

- **Wing Loading (W/S)**: Aircraft weight divided by wing area. A fundamental parameter influencing lift capability, stall speed, maneuverability, and gust response. Lower W/S generally means lower stall speed and better takeoff/landing, but may imply a larger wing. Units: N/m^2 or lbf/ft^2.
- **Thrust-to-Weight Ratio (T/W)**: Maximum thrust available divided by aircraft weight. A measure of acceleration capability. Higher T/W means better takeoff and climb. Dimensionless.

3.2.2 The Constraint Diagram

A 2D plot is created, commonly with W/S on the x-axis and T/W on the y-axis. Each performance requirement (e.g., "take off in under 100 ft") defines a curve on this plot. The area that satisfies all constraints simultaneously is the **"feasible design space."** The goal is to select an optimal design point—often at a corner of this feasible region—that represents the best trade-off for the mission.

3.2.3 A Few Constraint Equations (Gudmundsson's Methodology, Section 3.2.1)

Note: Equations can be different and may not match when comparing different textbooks These equations plot $T/W = f(W/S)$ to find the T/W needed for a given W/S to meet a specific performance requirement. (Refer to Chapter 3 of Gudmundsson for more Constraint Equations and information)

1. T/W for Desired Take-Off Ground Run Distance (S_G)

$$\frac{T}{W} = \frac{1.21}{g\rho C_{L_{max,TO}} S_G}\left(\frac{W}{S}\right) + \frac{0.605}{C_{L_{max,TO}}}(C_{D_{TO}} - \mu C_{L_{TO}}) + \mu$$

where $C_{L_{max,TO}}$ is max lift coefficient in takeoff configuration, $C_{D_{TO}}$ and $C_{L_{TO}}$ are drag and lift coefficients during ground run, μ is ground friction, g is gravity, ρ is air density.

2. T/W for a Desired Rate of Climb (V_V)

$$\frac{T}{W} = \frac{V_V}{V_\infty} + \frac{q}{W/S}C_{D_{min}} + \frac{k}{q}\left(\frac{W}{S}\right)$$

where V_V is rate of climb, V_∞ is climb speed, $q = \frac{1}{2}\rho V_\infty^2$ is dynamic pressure, $C_{D_{min}}$ is parasite drag coefficient, and $k = 1/(\pi e AR)$ is the induced drag factor.

3. T/W for a Desired Maximum Angle of Climb (γ)

$$\frac{T}{W} = \sin\gamma + \frac{1}{(L/D)_{max}} \approx \sin\gamma + \sqrt{4kC_{D_{min}}}$$

where $(L/D)_{max}$ is the maximum lift-to-drag ratio.

4. T/W for a Level Constant Velocity Turn (Load Factor n)

$$\frac{T}{W} = q\left[\frac{C_{D_{min}}}{W/S} + k\left(\frac{n}{q}\right)^2\left(\frac{W}{S}\right)\right]$$

where $n = 1/\cos\phi$ is the load factor due to bank angle ϕ.

5. T/W for a Climbing Constant Velocity Turn ($P_S = V_V$)

$$\frac{T}{W} = q\left[\frac{C_{D_{min}}}{W/S} + k\left(\frac{n}{q}\right)^2\left(\frac{W}{S}\right)\right] + \frac{P_S}{V_\infty}$$

6. T/W for a Desired Cruise Airspeed (V_C) (Same as level turn with $n = 1$)

$$\frac{T}{W} = q_C\left[\frac{C_{D_{min}}}{W/S} + \frac{k}{q_C^2}\left(\frac{W}{S}\right)\right]$$

where $q_C = \frac{1}{2}\rho V_C^2$.

7. T/W for a Desired Service Ceiling (Altitude where max rate of climb is $\approx$ 100 ft/min or 1.667 ft/s)

$$\frac{T}{W} = \frac{1.667}{V_Y} + \frac{q_{V_Y}}{W/S}C_{D_{min}} + \frac{k}{q_{V_Y}}\left(\frac{W}{S}\right)$$

where V_Y and q_{V_Y} are at service ceiling altitude.

8. T/W for a Desired Cruise Lift-to-Drag Ratio ($(L/D)_C$)

$$\frac{T}{W} = \frac{1}{(L/D)_C}$$

9. W/S for a Target Total Landing Distance (S_{LDG}) This is primarily a W/S constraint, usually forming a vertical line on the constraint diagram ($W/S \leq$ value). The equation is complex, relating S_{LDG} to W/S, $C_{L_{max,landing}}$, etc.

Stall Speed Constraint (Revisited): This often sets a maximum W/S:

$$\frac{W}{S} = \frac{1}{2}\rho V_S^2 C_{L_{max}}$$

3.2.4 Executing the Constraint Analysis

1. Determine all performance requirements from the competition rules (takeoff distance, mission tasks, etc.).
2. Estimate the aircraft's preliminary aerodynamic parameters ($C_{L_{max}}$, C_{D0}, Aspect Ratio, etc.).
3. Plot all the relevant constraint lines on a T/W vs. W/S graph.
4. Identify the feasible design region that satisfies all constraints.
5. Select an optimal design point ($(W/S)^*$, $(T/W)^*$) from this region. This point defines the performance targets for your aircraft.

ADD IMAGE HERE (of the constraint diagram from Gudmundsson or Raymer)

3.3 Phase 2: Takeoff Weight (W_0) Estimation

With the target performance parameters ($(W/S)^*$ and $(T/W)^*$) now defined, we can perform an initial sizing analysis to estimate the total takeoff weight (W_0) required to meet these targets while carrying the mission payload.

3.3.1 The Fundamental Weight Equation

The takeoff weight (W_0) can be broken down into its main components:

$$W_0 = W_{payload} + W_B + W_{empty}$$

To solve this equation, we express the battery weight and empty weight as fractions of the total weight. For an RC aircraft ($W_{crew} = 0$):

$$W_0 = \frac{W_{payload}}{1 - (W_B/W_0) - (W_e/W_0)}$$

This equation forms the basis of the iterative sizing process. We need to estimate the empty weight fraction (W_e/W_0) and the battery weight fraction (W_B/W_0).

3.3.2 Estimating Empty Weight Fraction (W_e/W_0)

The empty weight fraction depends on the type of aircraft, its materials, and structural design. For initial estimates, it is best to use historical data from your team's previous competition aircraft. A detailed weight buildup from a preliminary CAD model is necessary for more refined estimates. The structural requirements implied by the wing loading (W/S) chosen in Phase 1 will influence this fraction; a higher wing loading means higher structural loads and potentially a higher empty weight fraction.

3.3.3 Estimating Battery Weight Fraction (W_B/W_0)

For an electric aircraft, the battery weight (W_B) depends on the total energy required for the mission and the battery's specific energy (ρ_B). The required energy is calculated by summing the energy needed for each phase of the mission (takeoff, climb, level flight, etc.), accounting for the efficiencies of the motor (η_m) and propeller (η_p).

$$\frac{W_B}{W_0} = \sum \left(\frac{W_B}{W_0}\right)_{segment} = \sum \frac{E_{A,segment}}{W_0 \cdot \eta_m \cdot \eta_p \cdot \rho_B}$$

The energy required for each segment is calculated based on the thrust required for that phase of flight. For example, for level cruise:

$$\left(\frac{W_B}{W_0}\right)_{Cruise} = \frac{V_{Cruise} \cdot t_{Cruise}}{(L/D)_{Cruise} \cdot \eta_m \cdot \eta_p \cdot \rho_B}$$

3.3.4 Iterative Solution for W_0

The process to find the converged takeoff weight is as follows:

1. Guess an initial takeoff weight, $W_{0,guess}$.
2. Using historical data, estimate the empty weight fraction (W_e/W_0). Calculate the empty weight: $W_e = (W_e/W_0) \cdot W_{0,guess}$.
3. Using the mission requirements and the guessed weight, calculate the required battery weight fraction (W_B/W_0) and the battery weight: $W_B = (W_B/W_0) \cdot W_{0,guess}$.
4. Calculate a new takeoff weight using the weight equation: $W_{0,new} = W_{payload} + W_B + W_e$.
5. Compare $W_{0,new}$ with $W_{0,guess}$. If they are not close, set $W_{0,guess} = W_{0,new}$ and repeat the process from step 2 until the weight converges.

3.4 Initial Geometry Layout and Key Parameter Determination

Once the takeoff weight (W_0) is estimated and a design point ($(W/S)^*$, $(W/P_{SL})^*$ or $(T/W)^*$) is chosen from the constraint analysis, the next steps involve translating these overall parameters into a physical aircraft layout.

3.4.1 Determining Key Aircraft Performance Parameters

From the sizing process so far:

- **Wing Area (S)**: This is directly calculated from the chosen wing loading and the estimated takeoff weight: $S = W_0/(W/S)^*$.
- **Required Sea-Level Shaft Power (P_{SL})** (if using W/P framework): The motor's required power is $P_{SL} = W_0/(W/P_{SL})^*$. This value is necessary for selecting an appropriate electric motor.
- **Required Thrust (T_{req})** (if using T/W framework): The required thrust is $T_{req} = W_0 \cdot (T/W)^*$. For takeoff, specifically, the static thrust capability of the chosen motor-propeller combination must meet or exceed the thrust required by the takeoff constraint at the design $(W/S)^*$.

3.4.2 Fuselage Sizing

While Raymer provides statistical equations for fuselage length ($L_{fus} = aW_0^C$) for general aviation aircraft, for us, the fuselage design is more often driven by practical considerations:

- **Payload Bay**: The dimensions and volume required by the competition rules for the payload are primary drivers.
- **Component Layout**: Efficient and accessible placement of the battery, motor,ESC , receiver, and servos.
- **Center of Gravity (CG) Management**: The fuselage length and component placement are critical for achieving the desired CG range with and without payload.

- **Structural Integration**: Providing strong mounting points for the wing, landing gear, and empennage. The fuselage must have good longitudinal rigidity as well, which depends on moments of area, which also affect size. There must also be enough space to fit structural elements, main one is the wing spar which often crosses exactly where the payload is supposed to be.
- **Aerodynamics**: While a perfectly streamlined shape might be complex, minimizing frontal area and ensuring smooth transitions can reduce drag.

3.4.3 Wing Geometry

With the wing area (S) determined:

- **Aspect Ratio (AR)**: This is a key design choice, $AR = b_W^2/S$, where b_W is the wingspan. It involves a trade-off:
  - Higher AR (long, slender wings) generally reduces induced drag (drag due to lift), which is beneficial for climb and endurance.
  - However, higher AR wings tend to be structurally heavier for the same wing area (due to larger bending moments at the wing root) and can be more prone to stall at the wingtips if not designed carefully.
  - For RC payload lifters, AR values typically range from 6 to 10.
- **Wingspan (b_W)**: Calculated from AR and S: $b_W = \sqrt{AR \cdot S}$. Must comply with any wingspan limitations in the competition rules.
- **Mean Aerodynamic Chord ($\bar{c}_W$)**: This is the average chord length of the wing. For a simple rectangular wing, $\bar{c}_W = S/b_W =$ chord. For a tapered wing (where the tip chord c_{tip} is smaller than the root chord c_{root}, and $\lambda = c_{tip}/c_{root}$ is the taper ratio), a common formula is $\bar{c}_W = \frac{2}{3}c_{root}\frac{1+\lambda+\lambda^2}{1+\lambda}$. The MAC is important for aerodynamic calculations and tail sizing.
- **Planform Shape**: Common choices are rectangular (simplest to build, often good stall characteristics if the root stalls first) or tapered (more aerodynamically efficient by approximating an elliptical lift distribution, reducing induced drag, but more complex to build and these tend to tip stall).

3.4.4 Tail Sizing (Horizontal and Vertical Stabilizers)

The tail surfaces (empennage) provide stability and control. The tail volume coefficient method is a common approach for initial sizing. This empirical method relates the tail's size and its moment arm (distance from aircraft CG to the tail's aerodynamic center) to the wing's characteristics.

- **Horizontal Tail Volume Coefficient (c_{HT})**: This dimensionless coefficient relates the horizontal tail's effectiveness in providing pitch stability to the wing's pitching moment characteristics.

  $$c_{HT} = \frac{L_{HT}S_{HT}}{\bar{c}_W S_W}$$

  From this, the required Horizontal Tail Area S_{HT} can be estimated:

  $$S_{HT} = \frac{c_{HT}\bar{c}_W S_W}{L_{HT}}$$

- **Vertical Tail Volume Coefficient (c_{VT})**: This relates the vertical tail's effectiveness in providing yaw (directional) stability to the wing's yawing moment characteristics (often due to sideslip or asymmetric power).

$$c_{VT} = \frac{L_{VT} S_{VT}}{b_W S_W}$$

So, the required Vertical Tail Area S_{VT} is:

$$S_{VT} = \frac{c_{VT} b_W S_W}{L_{VT}}$$

In these equations:

- $S_W, b_W, \bar{c}_W$ are the wing area, wingspan, and mean aerodynamic chord.
- L_{HT} and L_{VT} are the moment arms from the aircraft's overall Center of Gravity (CG) to the aerodynamic center of the horizontal and vertical tail surfaces, respectively (There are other methods mentioned in other books as well). These are estimated from the aircraft's layout (fuselage length, wing position, tail position).
- c_{HT} and c_{VT} are empirical (historical) coefficients that vary by aircraft type. Raymer (Table 6.4) provides typical values (e.g., for a general aviation single-engine aircraft, $c_{HT} \approx 0.7 - 0.9$ and $c_{VT} \approx 0.04 - 0.07$; for sailplanes $c_{HT} \approx 0.5$, $c_{VT} \approx 0.02$).

For us, these coefficients provide a good starting point for tail sizing. The actual moment arms (L_{HT}, L_{VT}) are very sensitive to CG location, which in turn is affected by payload and battery placement. Tail sizes must be adequate to ensure good static and dynamic stability, often verified using tools like XFLR5 or by calculating the static margin.

3.4.5 Control Surface Sizing

Control surfaces (ailerons, elevator, rudder) allow the pilot to maneuver the aircraft. Initial sizing guidelines (from Raymer):

- **Ailerons (for roll control)**: Typically, the aileron chord is about 15-25% of the local wing chord. They usually span from about 50% of the wing's semi-span (half-span) out to about 90-95% of the semi-span, located on the outboard portion of the wing.
- **Elevator (for pitch control, on the horizontal tail)**: Typically, the elevator chord is about 25-50% of the horizontal tail's local chord. It usually spans most of the horizontal tail's span.
- **Rudder (for yaw control, on the vertical tail)**: Typically, the rudder chord is about 25-50% of the vertical tail's local chord. It usually spans most of the vertical tail's height.

These are initial estimates. The final sizes are determined by the control authority needed, which is assessed through more detailed stability and control analysis to ensure the aircraft is responsive and can recover from disturbances.

3.5 Introduction to Design Optimization (Condensed)

After establishing a basic aircraft size and layout, the design process often involves "optimization." Simply put, optimization is trying to make your design the "best" it can be for the specific mission, according to a defined set of criteria.

3.5.1 Core Concepts in Optimization

- **Objective Function**: This is the specific quantity you are trying to maximize (like competition score or payload capacity) or minimize (like empty weight or takeoff distance). For competitions, the scoring formula from the competition rules often serves as the primary objective function.
- **Design Variables**: These are the aspects of the aircraft that you, the designer, can change or adjust to improve the objective function. Examples include wing area, wingspan, choice of airfoil, motor type, propeller dimensions, material thicknesses, etc.
- **Constraints**: These are the rules or limitations that your design must adhere to. They define the boundaries of what's permissible. Examples include maximum dimensions mentioned in the competition rules, the required takeoff distance, material strength limits (e.g., the wing spar must not break under expected loads), or minimum stability requirements. The collection of all design choices that satisfy these constraints forms the "feasible region."
- **Finding the Optimum and Trade-offs**: The goal of optimization is to find the specific set of design variables within the feasible region that gives the best possible value for your objective function. This often involves making **trade-offs**, as improving one aspect of the design (like increasing wing area to lift more) might negatively impact another (like increasing drag or structural weight).

3.5.2 Optimization Approaches

While highly complex mathematical optimization algorithms exist, teams can employ practical methods to refine their designs, and MATLAB is a powerful tool for implementing these:

Parametric Sweeps (Trade Studies) via MATLAB: This is a very effective technique. You can write MATLAB scripts to systematically vary one or two design variables over a range (e.g., wingspan from X to Y meters, aspect ratio from A to B). For each combination:

- Calculate relevant performance metrics (e.g., $C_{L_{max}}$, drag, structural weight, takeoff distance, potential payload, and finally, the estimated competition score).
- Check if all constraints (rule compliance, structural limits) are met.
- Plot the results (e.g., Score vs. Wingspan) to visualize trends and identify regions that yield good performance. This helps in understanding design sensitivities and making informed choices. MATLAB's plotting capabilities are excellent for visualizing these trade spaces.
- **Penalty Functions**: When performing optimizations (even with parametric sweeps), if a design configuration violates a critical constraint (e.g., exceeds takeoff distance), you can conceptually apply a "penalty" to its calculated score in your MATLAB evaluation. This means such a design would rank poorly, effectively guiding your search towards feasible and high-performing solutions. For example, Gudmundsson mentions using a penalty function to disfavor wing taper ratios that lead to poor stall characteristics when optimizing for range.

Even if not implementing a formal optimization algorithm, the iterative process of defining an objective, changing variables, and evaluating against constraints using tools like MATLAB helps in converging towards a better design.

This initial sizing and basic optimization thinking, combining estimations, constraint satisfaction, and geometric layout, lays a quantitative groundwork before committing to detailed design and manufacturing for the aircraft.

4 Aircraft Configuration Layout

The selection of an aircraft's overall configuration layout is one of the earliest and most impactful decisions in the conceptual design phase. It involves choosing the arrangement of major components like wings, tail, fuselage, engine, and landing gear. This process is often more qualitative than quantitative at this early stage, relying on the mission requirements, applicable rules (like the competition rules), and insights from historical aircraft designs.

4.1 Introduction to Configuration Layout (Brief Overview)

A well-defined mission (how far, fast, high, what payload, operational profile) is critical before selecting a configuration. The designer must also understand how regulations or competition rules will influence choices (e.g., size limits, safety requirements).

The general philosophy for designing a "good" aircraft often emphasizes :

- **Essential Requirements**: Focus on what's truly needed and omit non-essentials.
- **Efficiency**: Minimize weight and drag to enhance performance.
- **Simplicity**: Simple designs are often lighter, cheaper, more reliable, and easier to develop.
- **Reliability and Maintainability**: Design for dependability and ease of repair.

Aircraft design has seen various trends or "fashions" over the decades (e.g., biplanes in the early era, sleek jets later) . However, functional considerations driven by the mission and technology are paramount. Understanding the basic components of an aircraft (wings, fuselage, empennage, powerplant, landing gear) is fundamental before delving into different layouts.

4.2 Fundamentals of Configuration Layout: Choices and Implications

This section explores key configuration choices, discussing their advantages and disadvantages. When faced with multiple viable options, a decision matrix can be a helpful tool to make a more objective choice based on different weighted criterion.

4.2.1 Vertical Wing Location

The wing's vertical position on the fuselage (high, mid, low, shoulder, or parasol) has significant impact on the aircraft performance.

- **High Wing**:
  - *Pros*: Good downward visibility; can allow for shorter, lighter landing gear if engines are wing-mounted (though less common for single-engine RC); often simpler gravity-fed fuel systems in GA (less relevant for electric RC); often good inherent roll stability (dihedral effect); less susceptible to ground effect during landing; good ground clearance for wings/props on rough fields .
  - *Cons*: Upward visibility obstructed, especially in turns; wing structure might pass through the cabin/fuselage if not carefully designed, or require external struts which adds drag.
  - *RC Aircraft Context*: Very popular for payload lifters due to unimpeded area under the wing for payload attachment/dropping, good ground clearance, and stable flight characteristics. Strut-bracing is common to save wing weight.
- **Low Wing**:

- *Pros*: Good upward visibility and into turns; often allows for shorter, simpler, and lighter landing gear that retracts into the wing; wing spar can pass under the cabin floor, leaving cabin unobstructed.
- *Cons*: Poor downward visibility; more susceptible to ground effect during landing (can cause floating); reduced ground clearance for wings/props; typically requires more geometric dihedral for roll stability .
- *RC Aircraft Context*: Can be used if payload is fuselage-internal or top-mounted. Simpler landing gear attachment to the wing can be an advantage.

- **Mid Wing**:
  - *Pros*: Potentially lowest interference drag between wing and fuselage; neutral roll stability (often favored for aerobatic aircraft) .
  - *Cons*: Wing spar passes directly through the middle of the fuselage, which can be very inconvenient for internal layout (payload, battery) unless the fuselage is very large or components are arranged around it .
  - *RC Aircraft Context*: Less common for payload missions due to fuselage obstruction.
- **Shoulder Wing**: Wing mounted on the upper part of the fuselage. A compromise offering some benefits of high and mid-wing.
- **Parasol Wing**: Wing mounted above the fuselage on struts or a pylon .
  - *Pros*: Aerodynamically "cleaner" as fuselage interference is minimized.
  - *Cons*: Structurally more complex due to struts/pylon; potential for increased interference drag at strut/fuselage and strut/wing junctions; can have excessive dihedral effect requiring larger tail surfaces .
  - *RC Aircraft Context*: Extremely Rare, but could be considered for unique designs aiming for minimal wing-fuselage interference.

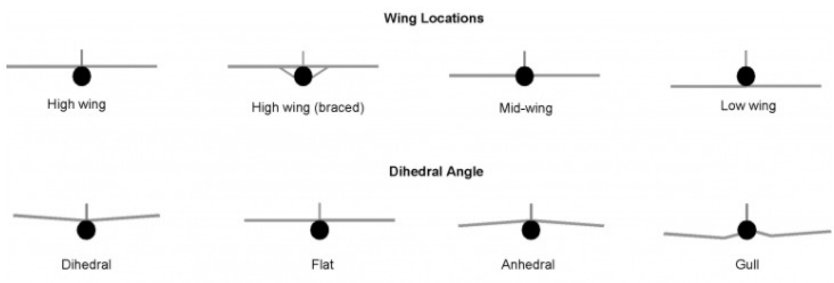


Figure 3: Common Vertical Wing Locations. (Source: Embry-Riddle Aeronautical University, Introduction to Aerospace Flight Vehicles)

4.2.2 Wing Dihedral and Anhedral

Dihedral is the upward angle of the wings from root to tip when viewed from the front; anhedral is the downward angle .

- *Effect*: Primarily influences lateral (roll) stability, specifically the dihedral effect ($C_{l\beta}$ – how the aircraft rolls in response to a sideslip) .

- **Dihedral (Positive Γ)**: When the aircraft sideslips (e.g., due to a rudder input or a gust), the oncoming airflow strikes the lower (into-the-slip) wing at a slightly higher effective angle of attack and/or with greater effect due to shielding by the fuselage, generating more lift on that wing. This creates a rolling moment that tends to level the wings, enhancing stability .
  - *Pros*: Increases roll stability, makes the aircraft easier to fly, helps coordinate turns.
  - *Cons*: Too much dihedral can make the aircraft overly stable and sluggish in roll, or lead to "Dutch Roll" oscillations (a coupled yawing and rolling motion).
  - *RC Aircraft Context*: Some dihedral is usually desirable for good handling, especially for less experienced RC pilots. High-wing aircraft often require less geometric dihedral because the high wing position itself contributes positively to the dihedral effect .
- **Anhedral (Negative Γ)**:
  - *Pros*: Reduces roll stability. Used on aircraft that are inherently too stable (e.g., very high wing or highly swept wings on some jets) to improve roll rate or counteract excessive dihedral effect. (Ex. on the Military Transport aircraft)
  - *Cons*: Can make the aircraft less stable or even unstable in roll if not carefully designed.
  - *RC Aircraft Context*: Less common for typical payload lifters, but might be seen on highly maneuverable RC aerobatic planes or if a high-wing design has an overly strong dihedral effect.
- *Variations*: "Cranked dihedral" (dihedral only on outboard wing sections), "gull-wing," or "inverted gull-wing" are less common and usually chosen for specific reasons like propeller clearance or engine placement. These are a pain to manufacture as well.

4.2.3 Wing Configuration

This refers to aspects like the number of wings and their general shape (excluding sweep for our low-speed context) .

- **Monoplane**: Single wing. By far the most common due to its overall aerodynamic efficiency and structural simplicity compared to multi-wing setups .
  - *Planforms*:
  - *Rectangular*: Easiest to build, often good-natured stall if the root stalls first. Aerodynamically less efficient (higher induced drag) than tapered wings for a given span.
  - *Tapered*: More aerodynamically efficient (slightly closer to elliptical lift distribution). More complex to build ribs.
  - *Elliptical*: Most efficient for induced drag, but very complex to build.
- **Biplane/Triplane**: Two or three wings stacked vertically. (Not for us due to the short timeframe)
- **Canard/Tandem Wing**:
  - *Canard*: Small lifting surface at the front, main wing at the rear. Can offer benefits in trim drag and CG range . The forward surface is often destabilizing longitudinally, requiring careful main wing design for overall stability.

– *Tandem Wing*: Two main lifting surfaces of roughly similar size, one behind the other .
– *RC Aircraft Context*: Canards are sometimes explored for specific aerodynamic goals or unique aesthetics but add design and stability analysis complexity.

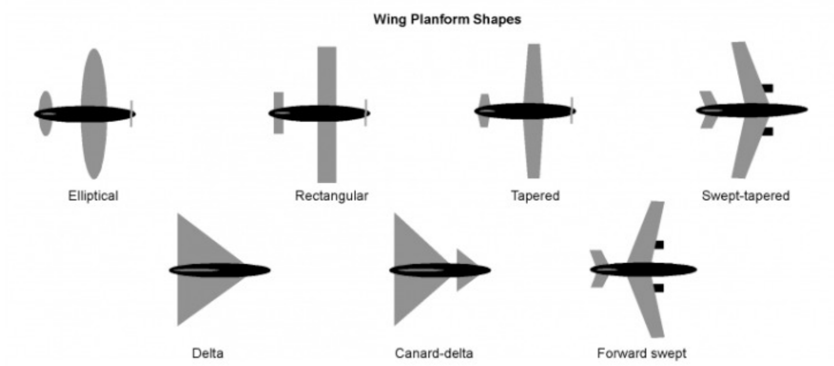


Figure 4: Common Wing Planform Types. (Source: Embry-Riddle Aeronautical University, Introduction to Aerospace Flight Vehicles)

4.2.4 Wing Structural Configuration

How the wing structure carries loads. Discussed further in Section 5.6.2

- **Cantilever Wing**: Wing structure is entirely self-supporting, attached only at the root to the fuselage.
- **Strut-Braced Wing**: Wing is supported by one or more external struts connecting the wing to the fuselage.

4.2.5 Fuselage Internal Layout

For RC aircraft, the fuselage interior housing contains the systems and payload (if any).

- **Accessibility**: This is necessary. Easy access to the battery (for quick changes), ESC, receiver, servos, and the payload mechanism is crucial. Hatches, removable sections, or well-designed internal bays are important.
- **Component Protection**: The fuselage should protect sensitive electronics and the battery from minor impacts, weather (if applicable), and dust/debris.
- **Cooling**: Adequate airflow for cooling the motor, ESC, and battery, especially if they are enclosed within the fuselage.
- **Payload Integration**: The fuselage must be designed to securely hold the payload as per competition rules, and allow for any required deployment mechanisms.
- **Structural Integrity**: The fuselage structure must be strong enough to carry the loads from the wing, tail, landing gear, payload, and battery, especially during hard landings or maneuvers.

4.2.6 Propulsion System Configuration (Propeller Motor Placement)

For RC electric propeller aircraft, key choices involve propeller type (tractor/pusher) and motor placement.

- **Propeller Type**:
  - **Tractor (Propeller at the Front)** :
    - *Pros*: Propeller operates in relatively undisturbed airflow (generally good efficiency); propwash over the wings and tail surfaces can enhance lift and control effectiveness at low airspeeds (e.g., during takeoff run or slow flight); often easier to achieve good motor cooling.
    - *Cons*: Can obstruct forward view if an FPV camera is nose-mounted; fuselage/components behind the prop experience turbulent propwash, which can increase drag on those parts.
  - **Pusher (Propeller at the Rear)** :
    - *Pros*: Can allow for a cleaner, more streamlined nose and fuselage ahead of the prop, potentially reducing overall parasite drag; offers an unobstructed forward view for FPV; may offer some protection to the propeller in certain crash scenarios (e.g., nose-first impact).
    - *Cons*: Propeller operates in the disturbed wake of the fuselage and/or wing, which can reduce propeller efficiency and increase noise; motor cooling can be more challenging if the motor is buried; can create complex aerodynamic interactions with the tail surfaces if they are in the direct propwash; can make hand-launching trickier if not designed carefully.
- **Motor Placement and Thrust Line**:
  - *Single vs. Twin Motors*: Most designs use a single motor for simplicity and weight. Twin motors offer redundancy and potentially more power/thrust but add significant weight, complexity (synchronization, ESCs), and cost. Differential thrust for yaw control is possible but rarely used.
  - *Thrust Line vs. Center of Gravity (CG)* : The vertical position of the motor's thrust line relative to the aircraft's CG significantly affects pitching moments when power is changed.
    - *High Thrust Line* (motor above CG): Increasing power tends to pitch the nose DOWN.
    - *Low Thrust Line* (motor below CG): Increasing power tends to pitch the nose UP.
  - Ideally, the thrust line should pass as close as possible to the CG to minimize these pitch changes. If a significant offset exists, angling the thrust vector slightly (up/down thrust) can help counteract these moments (as shown in Gudmundsson Fig 4-16), but this also has minor effects on effective thrust and lift components.

    ADD IMAGE HERE (from Gudmundsson of the motor placement and thrust line)
  - *RC Aircraft Context*: Tractor configurations are prevalent for simplicity and reliable performance. The thrust line is a key consideration for trim and handling; significant pitch changes with throttle are undesirable for precise flying.

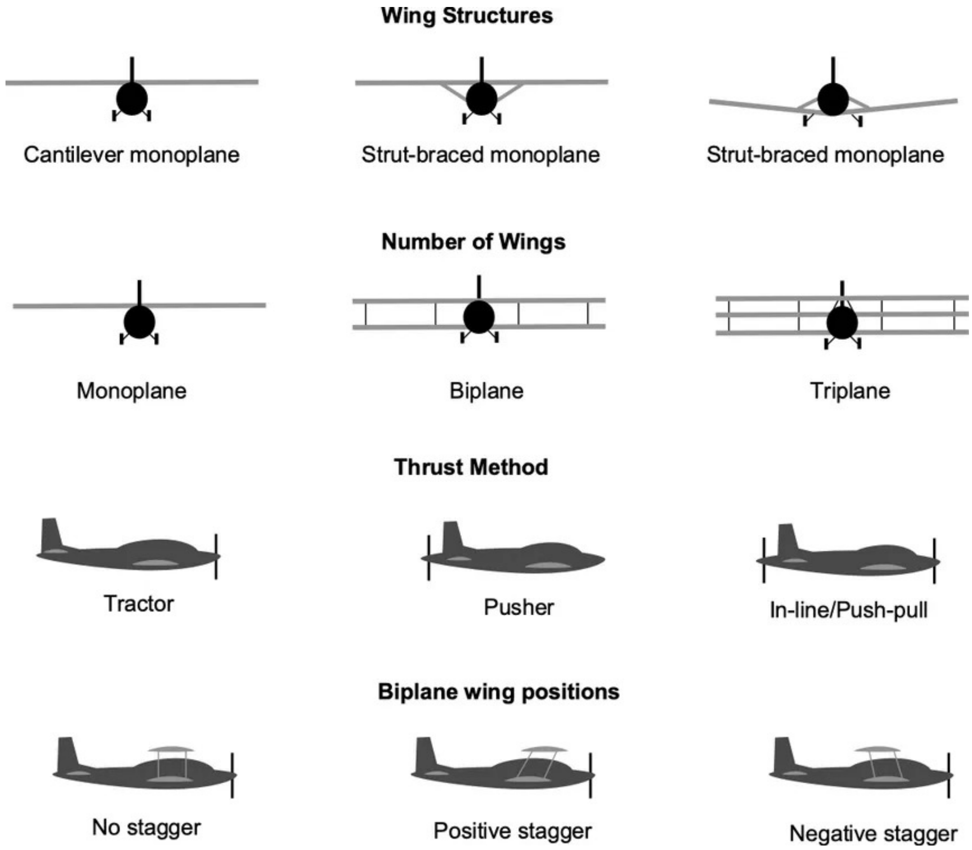


Figure 5: Propeller Configurations. (Source: Embry-Riddle Aeronautical University, Introduction to Aerospace Flight Vehicles)

4.2.7 Landing Gear Configuration

The landing gear configuration impacts ground handling, weight, drag, and suitability for different runway surfaces. The most common arrangements are the tricycle and taildragger configurations, though other types like bicycle (tandem) and single-wheel gears are also used in specialized designs. The choice of configuration has significant effects on ground stability, takeoff/landing characteristics, weight, drag, and suitability for different runway surfaces A detailed exploration of the pros, cons, and specific design considerations for each type is covered in Section 8.2.

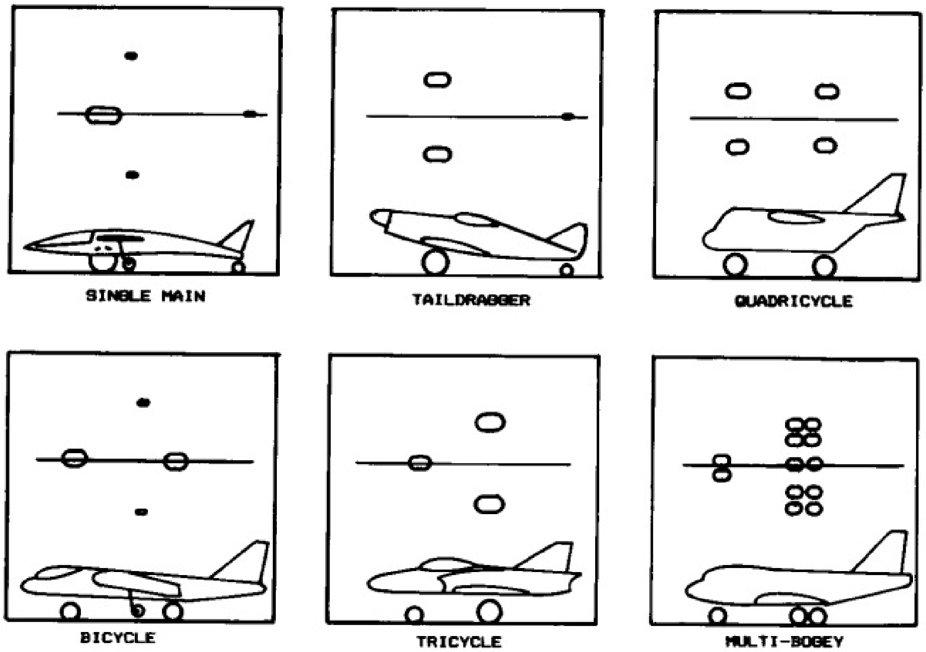


Fig. 11.1 Landing gear arrangements.

Figure 6: Common aircraft landing gear arrangements. (Source: Raymer, Ch 11, Fig. 11.1)

4.2.8 Tail Configuration

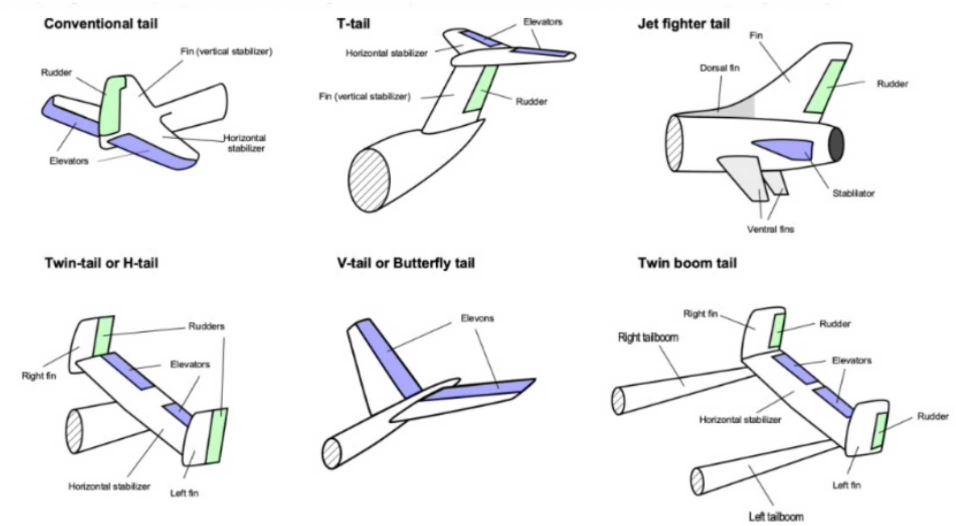
The arrangement of horizontal and vertical stabilizing surfaces significantly affects stability and control.

- **Conventional Tail**: Horizontal stabilizer and vertical fin at the rear of the fuselage .
  - *Pros*: Structurally simple, aerodynamically well understood, generally provides good stability and control.
  - *Cons*: The horizontal tail can be affected by the downwash of the wing or the slipstream of the propeller, which can alter its effectiveness.
- **T-Tail**: Horizontal stabilizer mounted on top of the vertical fin.
  - *Pros*: Keeps horizontal tail out of the wing's downwash and propeller slipstream, improving its effectiveness and reducing buffet; can act as an end-plate for the vertical fin, potentially increasing its effectiveness.
  - *Cons*: The vertical fin must be stronger (and thus heavier) to support the horizontal tail and resist flutter; can be susceptible to a "deep stall" on some aircraft if the main wing stalls at a high angle of attack and blankets the T-tail, making pitch recovery difficult; more complex structurally.
- **Cruciform Tail**: Horizontal stabilizer mounted partway up the vertical fin . A compromise between conventional and T-tail.
- **V-Tail**: Two tail surfaces angled upwards from the fuselage, combining the functions of horizontal and vertical stabilizers .
  - *Pros*: Potentially less wetted area and interference drag than conventional tail with two separate surfaces.

  - *Cons*: Control mixing (“ruddervators”) is required, which can be complex to set up mechanically or electronically; can have less control authority in combined pitch and yaw maneuvers compared to conventional surfaces; can be prone to Dutch roll if not properly designed.

- **H-Tail (Twin Vertical Tails)**: Two vertical fins, typically at the ends of the horizontal stabilizer .
  - *Pros*: Can provide good directional control, especially if one fin is in the slipstream of a propeller on a multi-engine aircraft (for engine-out situations); may allow for lower overall vertical tail height if fuselage length is restricted.
  - *Cons*: More wetted area and interference drag than a single vertical fin.

- *RC Aircraft Context*: The conventional tail is the most common for simplicity and reliable performance. T-tails are sometimes used to avoid propwash effects on the horizontal stabilizer. V-tails might offer slight drag/weight benefits, but require careful setup.



Different types of empennage designs. The conventional configuration has historically been the most popular.

Figure 7: Empennage (Tail) Configurations. (Source: Embry-Riddle Aeronautical University, Introduction to Aerospace Flight Vehicles)

4.2.9 Configuration Decision Matrix

When faced with multiple viable configuration options (e.g., high-wing tractor versus low-wing pusher), a decision matrix can be a useful tool for assisting in selection.

Process:

1. List the key design criteria or desirable features (e.g., ease of manufacturing, payload integration, stability, low drag, cost). Check the Project Plan document for a sample decision matrix

2. Assign a “weight” (importance factor) to each criterion based on team priorities and mission objectives.

3. Define several candidate aircraft configurations.

4. Score each configuration against each criterion (e.g., on a scale of 1-5, or 1-3 as in Table 4-3).

5. Calculate a weighted score for each configuration (sum of [criterion weight $\times$ criterion score]).

6. The configuration with the highest weighted score is notionally the “best” choice based on the defined criteria and weightings.

Note This method provides a structured solution and will force us to articulate and prioritize design goals. The outcome is subject to the selected criteria and their assigned weights, which can be subjective. Requires honest debate and consensus on these factors.
This systematic evaluation of configuration options, considering their pros and cons in the context of the mission and available resources, is vital for laying a strong foundation for the preliminary design.

5 Aircraft Structural Layout and Design

The structural design of an aircraft is paramount, ensuring it can withstand all anticipated loads during flight and ground operations while being as light as possible. This chapter explores fundamental concepts of structural layout, material selection, load considerations, and basic analysis techniques, drawing from Gudmundsson's primary text as well as key insights from Raymer's *Aircraft Design: A Conceptual Approach* and Bruhn's *Analysis and Design of Flight Vehicle Structures*.

5.1 Introduction: The Seven Links to Structural Integrity

A sound structural design considers several key aspects, often visualized as a chain of "Seven Links to Structural Integrity"; the entire design is only as strong as its weakest link.

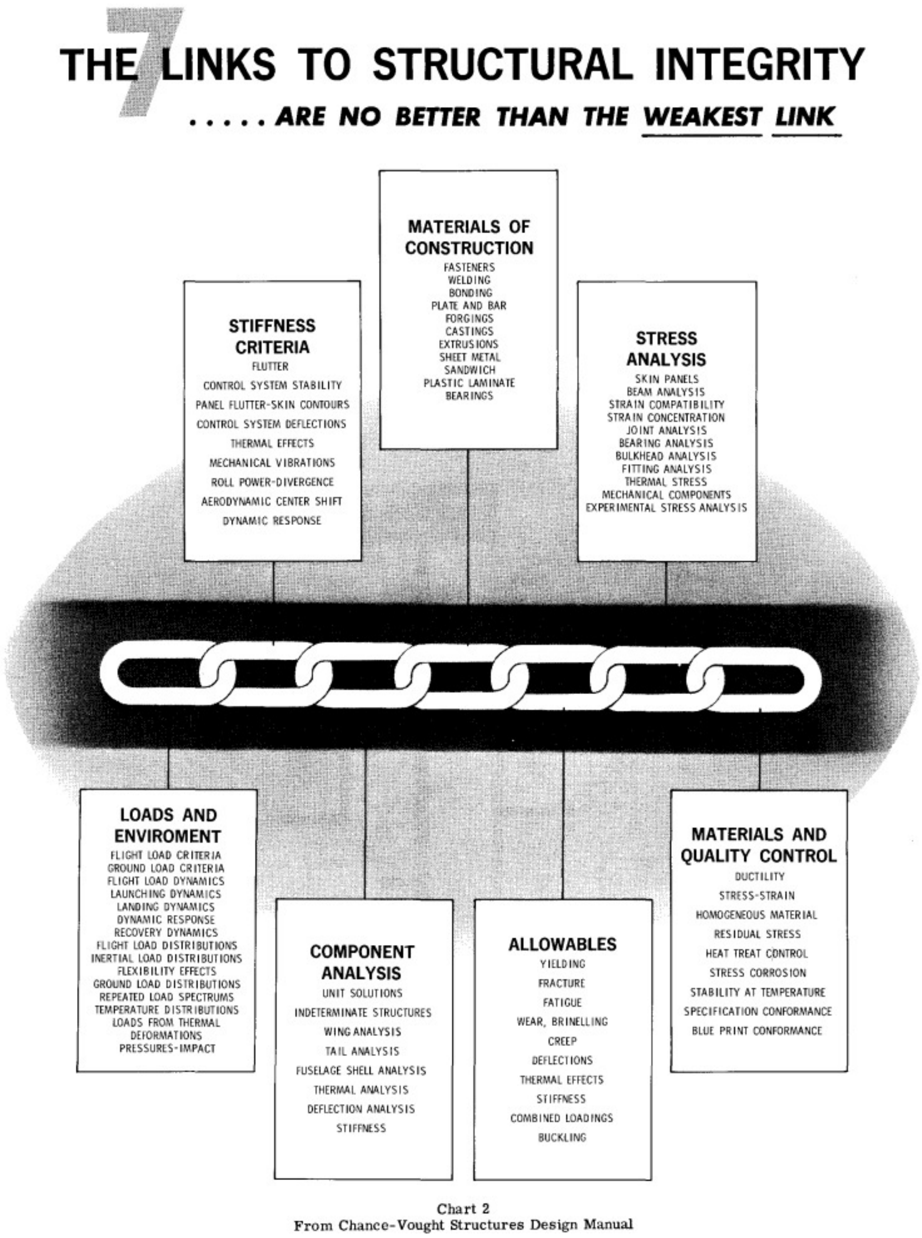


Figure 8: The Seven Links to Structural Integrity. (Source: Bruhn, E.F., Analysis and Design of Flight Vehicle Structures, Chapter A1, Chart 2)

Application to designing RC Aircrafts:

- **Stiffness**: Necessary for RC aircraft to:
  - Prevent flutter (rapid, destructive oscillations) of wings and control surfaces, especially for faster or larger models.
  - Maintain the intended aerodynamic shape of lifting surfaces under load for predictable performance.
  - Ensure control effectiveness by preventing linkages from deforming excessively.
- **Fatigue Life**: Generally of less concern for the short operational life of a competition aircraft. However, repeated high-stress events (like hard landings or motor vibrations) can lead to failures in joints or loosening of components.
- **Damage Tolerance through Stress and Component Analysis**: Highly relevant! Our aircraft will likely encounter rough handling. A design that can tolerate minor damage and be quickly repaired at the field offers a significant competitive advantage.
- **Producibility**: A major driver for our team. The structure must be buildable with our available skills, tools, and time. **A simpler, robust structure that is easy to build accurately is preferable to a complex one that is difficult to manufacture reliably.**

Fabrication methods like forging, casting, or extensive sheet metal work, common in full-scale aircraft, are generally not applicable to typical competition projects. Our focus is on woodworking, foam work, simple composites, and/ or 3D printing.

5.2 Understanding Loads on the Aircraft Structure

The structure must be designed to withstand all anticipated loads, multiplied by a safety factor.

- **Limit Load**: The maximum load the aircraft is expected to encounter in its service life. The structure should not have any permanent deformation up to this load.
- **Ultimate Load**: This is the limit load multiplied by the **Factor of Safety (FoS)**, which is typically 1.5 for aircraft structures (Should be higher for building RC planes due to manufacturing defects and us as students missing out on certain considerations / calculations). The structure must be able to withstand the ultimate load without failing.

5.2.1 Flight Loads: Maneuvers and Gusts

The V-n diagram (flight envelope diagram) defines the safe operating limits of airspeed (V) versus load factor (n). Load factor ($n = L/W$) is the ratio of lift to weight, expressing acceleration in G's. (For a detailed discussion, see Raymer, Chapter 14, pg. 336-341).

- **Maneuver Loads**: At low speeds, the maximum load factor is limited by the wing's stall angle of attack. At higher speeds, it is limited by structural strength. A key design point is the "high A.O.A." corner of the V-n diagram, where the aircraft reaches its maximum load factor at the lowest possible speed. At this high angle of attack, the lift vector can have a significant forward component, placing a forward-acting load on the wing structure.
- **Gust Loads**: A vertical gust (U) imposes a change in load factor, Δn, which can be estimated by:

  $$\Delta n = \frac{\rho U V C_{L\alpha}}{2(W/S)}$$

  (Source: Raymer, Eq. 14.4). This shows that lighter aircraft are more affected by gusts.

5.2.2 Ground Loads

- **Landing Loads**: Impact forces during touchdown are often the most critical loads an RC aircraft structure sees. Key landing loads include:
  - **Spin-up Load**: A large rearward force on the tires as they accelerate from zero rotation to ground speed upon contact.
  - **Spring-back Load**: A forward-acting load as the gear strut rebounds from the initial rearward spin-up deflection.
- **Taxiing Loads**: Forces from bumps and turns on the ground.

RC Aircraft Context: Landing loads are frequently the design driver for the landing gear, its mounting points, and the surrounding fuselage structure.

5.3 Materials for RC Aircraft Structures

Material selection is a key trade-off between strength, stiffness, weight, cost, and ease of fabrication.

- **Wood**:
  - *Balsa*: Excellent strength-to-weight ratio; used for ribs, formers, and sheeting.
  - *Plywood (Lite Ply, Aircraft Birch Ply)*: Stronger and more crush-resistant; used for firewalls, landing gear mounts, and spar webbing.
  - *Spruce/Basswood*: Good stiffness; used for longerons and spar caps.
- **Foams (EPS, XPS, EPP)**: Lightweight and easily shaped, but require reinforcement.
- **Composites**:
  - *Carbon Fiber (Rods, Tubes, Strips, Fabric)*: Extremely high strength and stiffness-to-weight ratios. Used for wing spars, reinforcements, and landing gear.
  - *Fiberglass (Cloth, Tape)*: Good strength, often used to reinforce foam cores or balsa structures.
- **Adhesives**: Cyanoacrylate (CA), Epoxy, and wood glues are essential. Proper joint preparation is vital.
- **Other Materials**: Metals for fasteners and linkages; 3D printed plastics (PLA, PETG, Nylon) for custom parts; heat-shrink films for covering.

5.4 Structural Arrangements and Basic Analysis for RC Aircraft

This section details common structural components and introduces the fundamental analysis methods used to ensure they are strong enough for their mission.

5.4.1 Wing Structures

The wing's primary job is to generate lift, and its structure must carry these aerodynamic loads to the fuselage. A typical wing consists of spars, ribs, and skin.

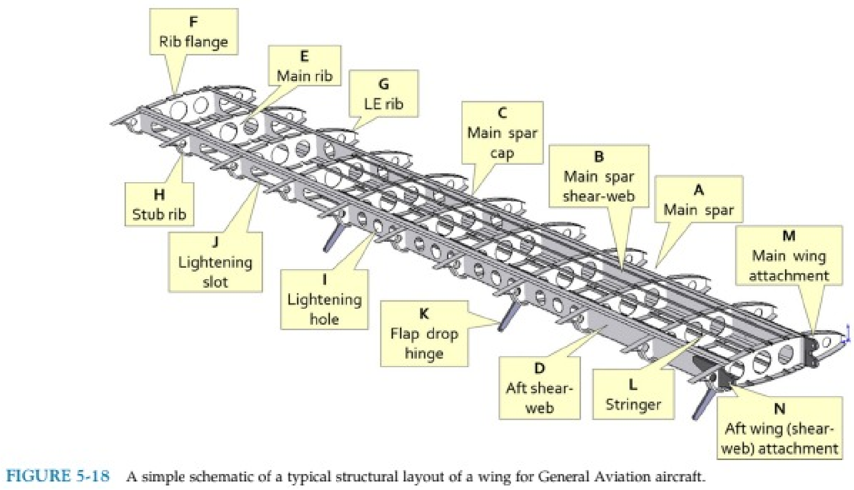


Figure 9: Common Internal Wing Structure Components. (Source: Gudmundsson, Ch 5, Fig. 5-18)

The components labeled in Figure 9 serve critical functions. The **Main Spar (A)** is the primary spanwise beam, consisting of a **Main spar shear-web (B)** and upper and lower **Main spar caps (C)**. It is designed to carry the majority of the wing's bending and shear loads. The **Aft shear-web (D)** is a secondary spar that helps close the structural box to resist torsion and supports the ailerons and flaps. **Ribs (E, G, H)** give the wing its airfoil shape and transfer loads from the skin to the spars. **Stringers (L)** are longitudinal stiffeners that prevent the skin from buckling. For a more detailed breakdown of each component's function, refer to Gudmundsson, Chapter 5, pg. 136-140.

- **Spars**: These are the most critical members in the wing. A thicker wing allows for a deeper spar, which is structurally more efficient (I increases with the cube of height) and can be made lighter for the same load-carrying capability. However, the tradeoff of a thicker wing is the increased induced drag.
- **Ribs**: These transverse members define the airfoil shape, transfer loads from the skin to the spars, and stabilize the entire structure against buckling. Rib spacing is a trade-off: closer ribs provide better support for the skin but add weight, while wider spacing saves weight but may allow the skin to buckle or sag. Using a simulation software can help define the number of ribs required based on a preliminary estimation.
- **Skin**: The outer covering of the wing. In a "stressed-skin" design, the skin carries a significant portion of the torsional and shear loads, forming a structural box with the spars. **RC Context**: Our wings are almost always stressed-skin designs. A common and very effective method is to use a main spar and a balsa-sheeted leading edge, forming a "D-box" tube that is very resistant to torsion.

5.4.2 Fuselage Structure

The fuselage is typically a semi-monocoque shell that connects the other components and houses the payload and systems.

Figure 10: Example of a Fuselage Truss Structure. (Source: Gudmundsson, Ch 5, Fig. 5-15)

- **Construction**: It is built from a framework of frames and bulkheads (for shape and concentrated loads) and longerons/stringers (for bending loads), covered by the skin.

- **Critical Areas**: Special attention must be paid to bulkheads at the firewall, wing attachments, landing gear mounts, and empennage mounts, as these transfer all the major loads into the fuselage structure. Cutouts for hatches and payload bays require reinforcement around their edges to manage stress concentrations.

5.4.3 Empennage (Tail) Structure

The horizontal and vertical tails are essentially smaller, simpler wings. Their structure is similar, often consisting of a single main spar, a few ribs to define the airfoil shape, and a skin covering.

5.5 Basic Structural Analysis

A brief overview of the fundamental analysis methods used to size structural members.

5.5.1 Truss Analysis (Method of Joints)

This method is used for analyzing truss structures like engine mounts. It relies on the principle that the sum of vertical and horizontal forces at each "joint" (or node) of the truss must be zero for the structure to be in equilibrium. By starting at a joint with only two unknown member loads, you can solve for those loads and proceed through the entire truss joint by joint. (For a detailed example, see Raymer, Chapter 14, pg. 378-380).

5.5.2 Beam Bending Analysis

This is the primary method for analyzing wing spars.

- **Shear and Bending Moment Diagrams**: First, the distributed lift and weight loads along the wing are converted into a shear force diagram and a bending moment diagram. The shear force at any point on the wing is the sum of all vertical loads outboard of that point. The bending moment is the integral of the shear force.
- **Bending Stress (σ)**: The tension and compression stresses in the spar caps due to the bending moment (M) are calculated using the flexure formula:

  $$\sigma = \frac{My}{I}$$

  (Source: Raymer, Eq. 14.35). Here, y is the vertical distance from the beam's neutral axis (centroid) and I is the beam's cross-sectional area moment of inertia. The highest stresses occur at the top and bottom surfaces.
- **Shear Stress (τ)**: The shear stress in the spar web is calculated using:

  $$\tau = \frac{VQ}{Ib}$$

  (Source: Raymer, Eq. 14.36). Here, V is the shear force, Q is the statical moment of area, I is the moment of inertia, and b is the width (thickness) of the web. For a simple I-beam spar, it's common to assume the web carries all the shear stress.

5.5.3 Buckling Analysis

Long, slender members under compression can fail due to buckling at a stress much lower than the material's compressive strength.

- **Column Buckling**: The critical buckling load (P_{cr}) for a strut or column is given by the Euler formula:
$$P_{cr} = \frac{\pi^2 EI}{L_e^2}$$
(Source: Raymer, Eq. 14.31). Here, E is the material's elastic modulus, I is the cross-section's moment of inertia, and L_e is the "effective length," which depends on how the ends are constrained (e.g., pinned, fixed).

- **Panel Buckling**: Flat sheets under compression or shear can also buckle. The critical buckling stress is given by:
$$F_{cr} = KE\left(\frac{t}{b}\right)^2$$
(Source: Raymer, Eq. 14.34). Here, t is the sheet thickness, b is the width of the panel, and K is a coefficient that depends on the panel's aspect ratio and how its edges are supported (e.g., clamped, simply supported), which can be found in charts like Raymer's Figure 14.33.

5.6 Applications: Structural Design Insights for Different Configurations

The choice of aircraft configuration (discussed in Chapter 4) is influenced by and influences the structural designs. Drawing conceptual inspiration from structural mechanics principles (as detailed in texts like Bruhn's *Analysis and Design of Flight Vehicle Structures*) can guide our structural decisions.

5.6.1 Empennage (Tail) Configurations

- **Conventional vs. T-Tail**: A T-tail (horizontal stabilizer on top of the vertical fin) requires a stronger, stiffer vertical fin to support the horizontal tail loads and resist flutter. The connection point is critical. Conventional tails have simpler load paths into the fuselage. (Source: Gudmundsson, Sec 5.3.3)
- **V-Tail**: The two surfaces carry combined pitching and yawing loads. During yaw maneuvers, one surface deflects up and one down, creating a significant torsional moment on the aft fuselage that must be resisted by a strong, stiff fuselage structure. (Source: Gudmundsson, Sec 5.3.3)
- **Boom-Mounted Tails (e.g., Twin Boom Fuselage)**: The booms act as cantilever beams supporting the tail surfaces, experiencing both bending and torsion. Their connection to the wing/main fuselage is a critical, high-stress area. The wing's center section must act as a strong, torsionally stiff box to handle these loads and prevent the booms from twisting relative to each other. (For further reading on beam and torsion analysis, see Bruhn, Chapters A5 and A6).

5.6.2 Wing Mounting and Bracing

- **Cantilever Wing**: All loads are transferred at the wing root. This requires very strong spars and a robust fuselage carry-through structure to distribute these concentrated loads.
  - *Pros*: Aerodynamically cleaner (lower drag as there are no external braces) .
  - *Cons*: Structurally heavier because the wing spar(s) must carry all bending and shear loads to the root, requiring a stronger and thus heavier spar system .
  - *RC Aircraft Context*: Common for smaller RC aircraft or where aerodynamic cleanness is important.

- **Strut-Braced Wing**: Struts significantly reduce the bending moment at the wing root, allowing for a lighter spar. However, the struts themselves are critical compression/tension members that must be analyzed for buckling. The spar itself is now a "beam-column," subjected to combined bending and axial compression from the strut, which requires a more advanced analysis. (For a detailed discussion on beam-columns, see Bruhn, Chapter A5, Art. A5.23).
  - *Pros*: Struts significantly reduce bending moments and shear forces in the wing spar at the root, allowing for a much lighter wing structure.
  - *Cons*: Struts add parasite drag.
  - *RC Aircraft Context*: Very common for high-wing RC payload lifters. The weight saving in the wing structure often outweighs the drag penalty, especially for aircraft designed for high lift at low speeds where induced drag is dominant.

Figure 11: Wing Attachment Methods. (Source: Gudmundsson, E.T., General Aviation Aircraft Design, Chapter 5, Fig. 5-14)

5.6.3 Pusher vs. Tractor Propulsion Mounting

- **Tractor**: Motor mount at the front of the fuselage. This is a relatively simple structure that must handle thrust, torque, and gyroscopic loads.
- **Pusher**: The motor is mounted at the rear, often on a pylon or between booms. This can involve a more complex mounting structure to transmit thrust to the airframe and to provide propeller clearance.

5.6.4 Cutouts and Access Hatches

Openings in the fuselage or wing skin (for payload bay, battery access, etc.) create stress concentrations and reduce structural stiffness.

- Reinforce edges of cutouts with doublers, stringers, or frames to restore strength and ensure load paths flow smoothly around the opening.

5.6.5 Joints and Connections

For built-up RC structures, joints are often the weakest points.

- Maximize glue surface area.
- Ensure a good fit of the parts before gluing.
- Use appropriate adhesives for the materials being joined.
- Gussets (small triangular pieces of ply or balsa) significantly strengthen corner joints.
- For high-load connections (e.g., wing-to-fuselage), joints with reinforcing plates (plywood, composite) are often used to distribute loads and prevent crushing of softer materials like balsa.

Applying these structural principles thoughtfully with adequate analysis will lead to a lighter, stronger, and more reliable aircraft for the competition.

6 Wing Design

The wing is the heart of the airplane. Its design dictates the cruise speed, takeoff and landing distances, stall speed, handling qualities, and overall aerodynamic efficiency. This chapter covers the selection of a 2D airfoil and the geometric properties that define the 3D wing. Other notable references are Prof. Canino's AAE334 notes, Anderson's *Introduction to Flight*.

6.1 The Anatomy of the Airfoil

An airfoil is the 2D cross-sectional shape of a wing. It is designed to generate lift more effectively than other shapes by creating a pressure difference between its upper and lower surfaces as it moves through the air. This pressure difference results from the air traveling faster over the curved upper surface than the flatter lower surface which, according to Bernoulli's principle, creates lower pressure on top and higher pressure on the bottom. The net result is an upward force.

6.1.1 Airfoil Terminology

To discuss airfoils, we need a common language. Figure 12 illustrates the key terms.

Raymer-Fig4.1.png

Figure 12: Key airfoil geometric parameters.

- **Chord Line**: A straight line connecting the leading edge (LE) and the trailing edge (TE). The length of this line is the **chord (c)**.
- **Mean Camber Line**: A line drawn halfway between the upper and lower surfaces. The curvature of this line defines the airfoil's camber.

- **Camber**: The maximum distance between the chord line and the mean camber line, expressed as a percentage of the chord. Camber is a primary driver of an airfoil's lifting capability and pitching moment.
- **Thickness**: The distance between the upper and lower surfaces. The maximum thickness as a percentage of chord (t/c) is a key design parameter. For RC aircraft, a thicker airfoil is often structurally more efficient, allowing for a deeper and lighter spar.
- **Leading Edge Radius**: The radius of the circle that defines the shape of the airfoil's nose. A larger, rounder leading edge generally leads to a gentler, more forgiving stall, which is a desirable characteristic.

6.1.2 Key Aerodynamic Coefficients

The forces and moments generated by an airfoil are represented by dimensionless coefficients. This allows us to compare different airfoils regardless of their size or the conditions they are tested in.

Gudmundsson-Fig8-5.png

Figure 13: A typical experimental lift curve (left) and drag polar (right) for a NACA 4415 airfoil.

- **Lift Coefficient (C_l):** The primary measure of an airfoil's ability to generate lift. It is plotted against the angle of attack (α) to create the lift curve.
- **Drag Coefficient (C_d):** Represents the profile drag of the airfoil, which is a combination of skin friction and pressure drag. The plot of C_l vs C_d is called the drag polar.
- **Pitching Moment Coefficient (C_m):** The moment that tends to rotate the airfoil. It is typically measured about the quarter-chord point (25% of the chord from the LE), where it remains relatively constant with changing angle of attack for most subsonic airfoils.

6.1.3 Pressure Distribution and the Pressure Coefficient (C_p)

The lift and pitching moment on an airfoil are generated by the pressure distribution over its upper and lower surfaces. This distribution can be conveniently described by the dimensionless **pressure coefficient,** C_p, defined as:

$$C_p = \frac{p - p_\infty}{q_\infty}$$

where p is the local static pressure at a point on the airfoil surface, p_∞ is the freestream static pressure, and q_∞ is the freestream dynamic pressure.

- A **negative** C_p indicates that the local pressure is lower than the freestream pressure. This "suction" effect on the upper surface of the airfoil generates the majority of the lift.
- A **positive** C_p indicates that the local pressure is higher than the freestream pressure. This occurs on the lower surface and at the stagnation point on the leading edge.

By plotting C_p around the airfoil contour, we get a clear picture of how lift is generated, as shown in Figure 14. The net aerodynamic force is the integral of this pressure distribution over the entire surface.

Basic_Aerodynamics-Fig4.30.png

Figure 14: A typical pressure coefficient distribution over an airfoil, illustrating the low-pressure region on the upper surface and high-pressure region on the lower surface that combine to create lift.

6.2 Airfoil Selection for RC Aircraft

For RC Aircraft competitions, selecting the right airfoil is a critical trade-off between maximizing lift, minimizing drag, ensuring gentle handling, and ease of construction.

6.2.1 The Importance of Reynolds Number (Re)

The Reynolds number ($Re = \rho V l/\mu$) is a dimensionless quantity describing the ratio of inertial to viscous forces in a fluid flow. It is critical because RC aircraft operate at a much lower Reynolds number than full-scale aircraft. An airfoil's performance, especially its drag and stall behavior, can change drastically at different Reynolds numbers. Therefore, we must select an airfoil that is designed for, or at least has predictable performance in, our operational Reynolds number range (typically 30,000 to 500,000). Many airfoils designed for full-scale aircraft perform poorly at these low Reynolds numbers, often suffering from "separation bubbles" near the leading edge that dramatically increase drag.

6.2.2 Selection Criteria

The airflow very close to the surface of a wing exists in a thin region is called the **boundary layer**. Within this layer, the flow can be either smooth and orderly (**laminar**) or chaotic and energetic (**turbulent**). As air flows from the leading edge toward the point of maximum thickness, it accelerates, and the pressure drops (a favorable pressure gradient). Past the point of maximum thickness, the airfoil's shape forces the flow to slow down and recover pressure to match the freestream pressure at the trailing edge. This region of increasing pressure (and decreasing velocity) is called an **adverse pressure gradient**.

This adverse pressure gradient pushes against the air in the boundary layer, slowing it down even more. If the adverse gradient becomes too strong (which happens as the angle of attack increases), the airflow in the boundary layer can stop or even reverse, causing the flow to detach from the surface. This is called **flow separation**, and when it becomes widespread, it causes the dramatic loss of lift known as an aerodynamic stall. With this in mind, the following criteria are critical for airfoil selection:

- **Maximum Lift Coefficient ($C_{l_{max}}$)**: A high $C_{l_{max}}$ is essential to achieve short take-off distances and low landing speeds. Many high-lift airfoils (e.g., from the Selig or Eppler series) are designed for this purpose.

- **Stall Characteristics**: A gentle stall helps for a predictable and pilot-friendly aircraft. We want an airfoil that gradually loses lift (trailing-edge stall) rather than abruptly (leading-edge stall). "Fat" airfoils with a larger leading-edge radius and thickness generally exhibit a gentler stall because the higher-energy turbulent boundary layer they promote can resist separation longer.

- **Pitching Moment Coefficient (C_m)**: A large negative pitching moment requires a larger horizontal tail to trim the aircraft, which adds weight and trim drag. We should favor airfoils with a low pitching moment (C_m close to zero). For tailless aircraft like flying wings, a reflexed airfoil with a near-zero or slightly positive pitching moment is required for stability.

- **Manufacturability**: As a student team, we must choose an airfoil that we can build accurately. Airfoils with complex curves, significant undercamber, or extremely sharp trailing edges are difficult to build with balsa wood and foam. Simpler airfoils, such as the Clark Y or the well-documented NACA series, are often easier to construct reliably.

6.2.3 Practical Airfoil Selection Process

A systematic process for selecting an airfoil for our RC aircraft can be as follows.

1. **Define Requirements**: Based on the competition rules and our design goals, determine the target cruise C_l, required $C_{l_{max}}$ for takeoff, and desired stall behavior.

2. **Search Databases**: Use online resources like the **UIUC Airfoil Coordinates Database** to find candidate airfoils that match our requirements (e.g., high-lift, low Reynolds number, specific thickness). These are typically stored as '.dat' files.

3. **Analyze with Software**: Use airfoil analysis software like **XFLR5** to analyze the candidate airfoils. These tools can import '.dat' files and generate lift curves and drag polars at our specific Reynolds numbers.

4. **Compare Performance**: Plot the results and compare the $C_{l_{max}}$, stall angle, drag at cruise C_l, and pitching moment for each candidate airfoil to see which best meets our goals. A decision matrix can be a useful tool for this comparison.

5. **Validate with Experimental Data**: This is a critical step. For your top 2-3 airfoil choices, search for real-world wind tunnel data or flight test results. Compare the software predictions from XFLR5 to this experimental data. An airfoil whose performance is validated by real-world tests is a much more reliable and a less risky choice.

6.2.4 Common Airfoil Families for RC Aircraft

- **NACA Airfoils**: The NACA (National Advisory Committee for Aeronautics) developed several systematic airfoil families.
  - **4-Digit Series (e.g., NACA 2412)**: The first digit is the maximum camber in percent chord, the second digit is the location of the maximum camber in tenths of chord, and the last two digits are the maximum thickness in percent chord. A NACA 0012 is a 12% thick symmetric airfoil, making it excellent for tail surfaces.
  - **5-Digit Series (e.g., NACA 23012)**: The first digit refers to the design lift coefficient, the next two digits define the maximum camber location, and the last two digits define the thickness. They were developed to move the maximum camber forward for greater maximum lift.
  - **6-Series (e.g., NACA $65_3 - 415$)**: The first "laminar flow" airfoils, designed to reduce drag. The numbering system indicates the series, chordwise location of minimum pressure, the range of lift coefficients with favorable pressure gradients, the design lift coefficient, and the thickness.
- **Clark Y**: An extremely popular early airfoil, famous for having a flat lower surface from about 30% chord aft, making it very easy to build for RC aircraft. It offers good lift and gentle stall characteristics.
- **Eppler and Selig Airfoils**: These are more modern airfoils specifically designed for high-lift, low Reynolds number applications, making them a good potential choice for RC aircrafts. Examples include Eppler 423 and Selig 1223.
- **Reflexed Airfoils (e.g., Horten series)**: These airfoils have a distinctive upward-curved (reflexed) trailing edge. This design produces a near-zero or slightly positive pitching moment, which is a requirement for tailless flying wing aircraft to be stable.

6.3 From 2D Airfoil to 3D Wing: Wingtip Vortices and Induced Drag

A wing is a 3D, finite-span surface. Its performance is fundamentally different from the 2D airfoil sections that define its shape. The primary reason for this difference is the effect of the wingtips. When a wing is generating lift, the pressure on the bottom surface is higher than on the top surface. Near the wingtips, this high-pressure air tends to spill around the tip to the low-pressure region above. This spanwise flow of air creates a powerful swirling motion that trails behind the wing, known as a **wingtip vortex**.

This vortex system imparts a downward velocity to the air flowing over and behind the wing. This downward component of velocity is called **downwash**.

The downwash has a critical effect: it changes the direction of the airflow that the wing experiences. The local relative wind is tilted downward. Because the total aerodynamic force is, by definition, perpendicular to the local relative wind, the downwash causes this force vector to be tilted backward. The component of this tilted aerodynamic force that is parallel to the freestream is called **induced drag** (D_i). It is the drag due to lift.

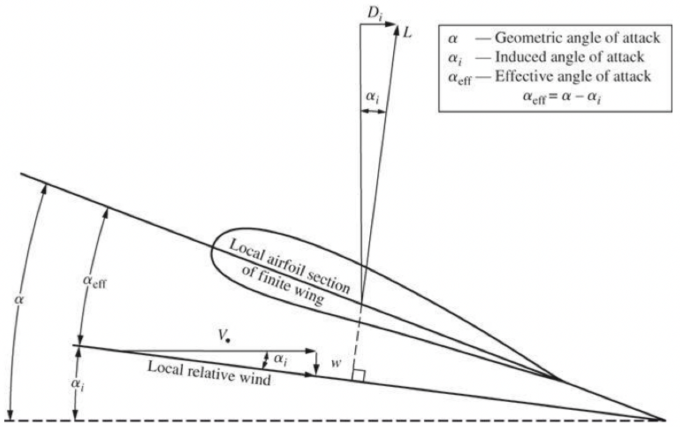


Figure 15: The effect of downwash is to tilt the total aerodynamic force vector backward, creating a component of that force in the drag direction. This is induced drag. (Source: Prof. Canino's 334 notes)

Quantitatively, the downwash results in an **induced angle of attack** (α_i), which is the angle by which the lift vector is tilted backward. For an ideal wing with an elliptical lift distribution, the induced angle of attack (in radians) is given by:

$$\alpha_i = \frac{C_L}{\pi AR}$$

For small angles, the induced drag coefficient is approximately equal to the lift coefficient multiplied by the induced angle of attack:

$$C_{D,i} \approx C_L \cdot \alpha_i$$

By substituting the expression for α_i into this relation, we arrive at the fundamental equation for induced drag for an elliptical wing:

$$C_{D,i} = \frac{C_L^2}{\pi AR}$$

Real wings that do not have a perfect elliptical lift distribution are less efficient, resulting in higher induced drag. This is accounted for by the **Oswald efficiency factor** (e), which leads to the general formula for the induced drag coefficient:

$$C_{D,i} = \frac{C_L^2}{\pi e AR}$$

To calculate the **induced drag force (D_i)**, you multiply the induced drag coefficient by the dynamic pressure and the wing's reference area. The formula is:

$$D_i = q_\infty S C_{D,i} = q_\infty S \left(\frac{C_L^2}{\pi e AR} \right)$$

6.4 Effective Angle of Attack and its Consequences

Due to downwash, the local airfoil sections of the wing do not see the freestream airflow directly. They operate at an angle of attack that is reduced by the **induced angle of attack (α_i)**.

- **Geometric Angle of Attack (α)**: Angle between the wing chord line and the direction of the free-stream velocity.
- **Induced Angle of Attack (α_i)**: Angle by which the downwash deflects the local airflow. It can be approximated as $\alpha_i \approx w/V_\infty$.
- **Effective Angle of Attack (α_{eff})**: The angle the airfoil section actually "feels." It is the geometric angle of attack minus the induced angle.

$$\alpha_{eff} = \alpha - \alpha_i$$

This relationship is fundamental. It means a 3D wing must fly at a higher geometric angle of attack (α) to achieve the same effective angle of attack (α_{eff}) and thus the same sectional lift coefficient (c_l) as its 2D airfoil counterpart. This directly leads to a reduced lift curve slope for the 3D wing ($C_{L\alpha}$) compared to the 2D airfoil ($c_{l\alpha}$).

6.5 Wing Lift and Drag Characteristics

The 3D effects of downwash and induced drag directly modify the performance characteristics of the wing compared to the airfoil data.

6.5.1 Wing Lift Curve Slope ($C_{L\alpha}$)

Due to the induced angle of attack, the lift curve slope of a finite wing ($C_{L\alpha}$) is always less than the lift curve slope of its 2D airfoil section (a_0). For an elliptically loaded wing, the relationship is:

$$C_{L\alpha} = a = \frac{a_0}{1 + a_0/(\pi \cdot AR)}$$

where a_0 is the 2D lift curve slope (theoretically 2π per radian) and AR is the aspect ratio. This equation shows that a higher aspect ratio results in a higher lift curve slope, closer to the 2D value.

6.5.2 Wing Drag Polar

The total drag of a wing is the sum of parasite drag (C_{D0}) and induced drag (C_{Di}). This relationship is described by the parabolic drag polar equation:

$$C_D = C_{D0} + C_{Di} = C_{D0} + \frac{C_L^2}{\pi e AR}$$

- **Parasite Drag (C_{D0})**: The drag of the aircraft at zero lift, composed of skin friction drag and form drag (due to separation).
- **Induced Drag (C_{Di})**: The drag due to lift. It is inversely proportional to the aspect ratio, meaning that wings with a higher aspect ratio have less induced drag for the same amount of lift.

- **Oswald Efficiency Factor** (e): A correction factor (typically 0.7-0.95) that accounts for the fact that a real wing's lift distribution is not perfectly elliptical, resulting in higher induced drag than the theoretical minimum.

Lecture13_Slide4_Combined.png

Figure 16: Effect of Aspect Ratio on the lift curve and drag polar. A higher AR wing has a steeper lift curve slope and less induced drag (a "narrower" drag polar) than a lower AR wing of the same airfoil and area.

6.6 Wing Planform Design and Trade-offs for RC Aircraft

The choice of the wing's planform shape is a critical decision that balances aerodynamic efficiency, stall characteristics, and manufacturability.

- **Rectangular Wing** ($\lambda = 1.0$):
  - **Pros**: Easiest and cheapest to build, as all ribs can be identical. It typically exhibits gentle stall characteristics, as the center of the wing tends to stall first. This makes

it a very strong choice for RC competitions where build time and simplicity are paramount.

  - **Cons**: Aerodynamically inefficient due to high induced drag.

- **Tapered Wing** ($0 < \lambda < 1.0$):
  - **Pros**: More efficient than a rectangular wing, offering lower induced drag and less structural weight because the bending moments are reduced. A taper ratio of about 0.45 produces a lift distribution very close to the elliptical ideal for an unswept wing.
  - **Cons**: More complex to build, as every rib is a different size. It is more prone to tip stall if not designed with sufficient washout.

- **Elliptical Wing**:
  - **Pros**: The most aerodynamically efficient planform, providing the minimum possible induced drag for a given aspect ratio because it generates an elliptical lift distribution.
  - **Cons**: Very difficult and expensive to manufacture accurately. The entire wing tends to stall at once, leading to an abrupt and potentially dangerous stall.

- **Delta Wing**:
  - **Characteristics**: A triangular planform used for supersonic aircraft. At high angles of attack, it generates powerful **leading-edge vortices** that create additional "vortex lift," allowing it to fly at very high angles of attack without the abrupt stall seen in conventional wings.
  - **RC Aircraft Context**: While stable at high angles of attack, its maximum lift coefficient is generally low, and it produces a lot of drag at low speeds. This makes it unsuitable for RC competitions focused on low-speed performance and heavy lifting.

6.7 High-Lift Devices: Flaps

To meet the demanding takeoff and landing requirements of RC aircraft competitions, we must generate as much lift as possible at low speeds. High-lift devices are essential for this purpose. Flaps are hinged surfaces on the trailing edge of the wing that are deflected downward to increase the wing's effective camber, resulting in a significant increase in the maximum lift coefficient ($C_{L_{max}}$).

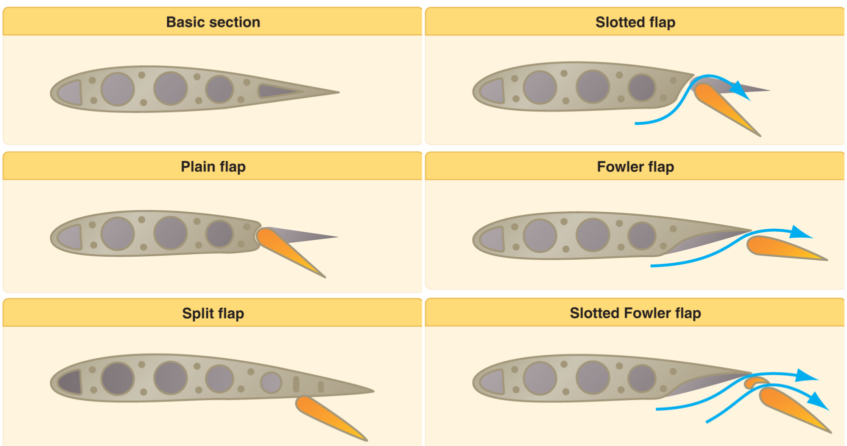


Figure 17: Common types of trailing-edge flaps.

- **Plain Flap**: The simplest type, where a portion of the trailing edge hinges downward.

- **Split Flap**: A plate that deflects from the lower surface of the wing, creating a large increase in lift but also a significant amount of drag.
- **Slotted Flap**: Designed with a gap that allows high-pressure air from below to energize the flow over the top of the flap, delaying separation and increasing lift.
- **Fowler Flap**: This flap moves rearward as it deflects downward, increasing both the wing's area and its camber. Fowler flaps are the most effective type but are also the most mechanically complex. (These are generally used in the large commercial airliners.)

RC Aircraft Context: For our competition, some form of flap system is necessary to adhere to a small take-off distance. Simple plain flaps are the easiest to build. Slotted flaps offer better performance and are a good intermediate complexity option. Fowler flaps, while offering the best performance, can be very challenging to implement reliably on an RC aircraft and they also add onto unnecessary weight.

6.8 Wing Design and Overall Aircraft Performance

While the wing's aerodynamic characteristics are critical, they must be considered within the context of the entire aircraft's performance and stability. The wing does not fly in isolation; it dictates the requirements for many other components and determines the aircraft's ability to complete its mission.

6.8.1 SLUF

The performance of an airplane is governed by the balance of four primary forces: **Lift**, **Weight**, **Thrust**, and **Drag**. For the most basic flight condition—**Steady Level Unaccelerated Flight (SLUF)**—the opposing forces are in equilibrium. This is the condition for cruise flight.

- **Lift = Weight** ($L = W$)
- **Thrust = Drag** ($T = D$)

The wing is the primary producer of lift, and a major contributor to the aircraft's total drag. Therefore, the wing's lift-to-drag ratio (L/D) is a key measure of its aerodynamic efficiency and a dominant factor in the aircraft's overall performance. Other performance metrics, such as rate of climb and glide ratio, are also heavily dependent on the wing's characteristics and will be analyzed in detail in later chapters.

6.8.2 Interaction with Other Components: The Tail

The wing's design has a profound impact on the rest of the airframe, particularly the tail surfaces. The initial design of the wing and tail can be approached separately using estimations, but they must ultimately be designed together as an integrated system to ensure the aircraft is stable and controllable.

The primary interactions are:

- **Pitching Moment**: The wing's airfoil creates a pitching moment (C_m) that must be counteracted by the horizontal tail to keep the aircraft's nose from pitching up or down. A wing with a large negative pitching moment requires a larger horizontal tail and/or a greater download on the tail to achieve balance, which increases both trim drag and overall weight.

- **Downwash**: The downwash generated by the wing's tip vortices strikes the horizontal tail, altering the local angle of attack that the tail experiences. This effect must be accounted for when determining the size and incidence angle of the tail to ensure proper stability.

Because of these strong interactions, the aircraft design process is iterative. An initial wing is designed, a tail is sized to match it, and then analysis is performed to see if the combination meets all stability and performance requirements. Adjustments to both the wing and tail are often necessary to find an optimal solution.

7 Tail Design

The tail, or empennage, is a critical set of surfaces located at the rear of the aircraft. While the wing generates the lift needed to fly, the tail provides the necessary stability and control to make the flight safe and manageable. This chapter outlines the fundamental functions of the tail and presents a process for its design, focusing on the concepts and calculations most relevant to RC aircraft. Another reference used in the making of this chapter is Chapter 6 from Sadraey's Aircraft Design Fundamentals.

7.1 Functions of the Empennage

The tail assembly consists of two primary surfaces: the **Horizontal Tail** (or horizontal stabilizer) and the **Vertical Tail** (or vertical stabilizer). Together, they perform three crucial functions:

1. **Stability**: The tail provides the aircraft with static stability, which is its natural tendency to return to its original flight path after being disturbed. It acts like the feathers on an arrow, ensuring the aircraft remains pointed in the right direction.

2. **Control**: The movable surfaces on the tail—the **elevator** on the horizontal tail and the **rudder** on the vertical tail—allow the pilot to maneuver the aircraft by creating moments around its center of gravity.

3. **Trim**: The tails are used to counteract the moments generated by other parts of the aircraft, primarily the wing. This is known as trim and being in the trim condition allows the aircraft to maintain a steady flight attitude (like level cruise) without requiring constant control input from the pilot.

7.2 Aircraft Trim and the Equations of Motion

An aircraft in flight is free to move in six different ways, known as the **6 Degrees of Freedom (6-DOF)**. These consist of three translational (linear) movements and three rotational movements about the aircraft's center of gravity (CG).

For an aircraft to be in a state of equilibrium—flying at a constant velocity without accelerating or changing its attitude—the sum of all external forces and all external moments acting on it must be zero. This gives us the six fundamental equations for trim:

- **Sum of Forces**:
  - $\Sigma F_x = 0$ (Forces in the direction of flight)
  - $\Sigma F_y = 0$ (Side forces)
  - $\Sigma F_z = 0$ (Vertical forces)
- **Sum of Moments about the Center of Gravity (CG)**:
  - $\Sigma L_{cg} = 0$ (Rolling Moment)
  - $\Sigma M_{cg} = 0$ (Pitching Moment)
  - $\Sigma N_{cg} = 0$ (Yawing Moment)

7.2.1 Longitudinal Trim: The Pitching Moment Balance

Longitudinal trim is the state of flight where the aircraft has no tendency to pitch up or down on its own. This is achieved when the sum of all pitching moments about the center of gravity (CG) is zero ($\sum M_{cg} = 0$). The primary forces and moments contributing to this balance are shown in Figure 18.

Sadraey_6_-_Tail_Design-Fig6.3.png

Figure 18: Forces and moments contributing to the longitudinal balance of an aircraft.

The complete equation for the summation of these pitching moments is:

$$\Sigma M_{cg} = M_{acwf} + M_{L_{wf}} + M_{L_h} + M_{fus} + M_{prop} = 0$$

For analysis, these physical moments are converted into non-dimensional coefficients. The process begins by expressing the major moment contributors in coefficient form:

- The inherent pitching moment of the wing-fuselage combination at its aerodynamic center (ac_{wf}) is:

$$M_{ac,wf} = qS\bar{c}C_{m_{acwf}}$$

- The moment generated by the lift of the wing-fuselage (L_{wf}) is:

$$L_{wf} = (qSC_{L_{wf}})x_{wf}$$

- The primary balancing moment generated by the lift of the horizontal tail (L_h) is:

$$M_{Lh} = L_h \cdot l_h = (qS_h C_{L_h}) \cdot l_h$$

$$Note : q = 1/2 \cdot V^2 \cdot \rho$$

By substituting these into the main moment equation and dividing the entire equation by $qS\bar{c}$, we arrive at the pitching moment equation in coefficient form. For the trim condition, this equation is set to zero. The following is the simplified final equation and is key for horizontal tail design. The complete steps for this derivation are provided in Chapter 6 of Sadraey's:

$$C_{m,acwf} + C_{L_{wf}} \cdot (h - h_o) - C_{L_h} \cdot \bar{V}_H = 0$$

Aircraft Design. (Note: M_{acwf} is the same as the $M_{o_{wf}}$ used in the Sadraey).

The goal of trim is to adjust the tail's lift force (L_h) via the horizontal tail and elevator so that the sum of these three moment groups is exactly zero for any given flight condition.

7.2.2 Directional and Lateral Trim

While an RC aircraft is built to be symmetric, forces from the propeller and side gusts can create yawing and rolling moments that need to be trimmed.

- **Directional Trim ($\Sigma N_{cg} = 0$)**: The primary force that must be trimmed in yaw for a single-engine prop plane is the **spiraling slipstream**. The propeller sends a rotating column of air back along the fuselage. This swirling flow strikes the side of the vertical tail, creating a force that pushes the tail to the side and yaws the aircraft's nose (typically to the left for a clockwise-rotating prop). This effect is countered by applying a small amount of steady right rudder trim or by mounting the vertical tail at a slight angle of incidence to create a counteracting force automatically during cruise.
- **Lateral Trim ($\Sigma L_{cg} = 0$)**: The rotation of the propeller also creates an equal and opposite **torque reaction** that tries to roll the aircraft in the opposite direction. This is most noticeable at high power and low airspeed. This rolling moment is trimmed by applying a small, constant aileron input or by physically rigging one wing to have slightly more lift than the other.

7.3 The Tail Design Process

The design of the tail is an iterative process of defining its geometry to meet stability and control requirements. The goal is to create the smallest and lightest empennage that can effectively stabilize and control the aircraft throughout its flight envelope.

7.3.1 Listing the Design Parameters

The complete design of the empennage requires defining the following parameters for both the horizontal (subscript h) and vertical (subscript v) tails:

- **Configuration and Location** (e.g., Conventional, T-tail, Canard)
- **Planform Area** (S_h, S_v)
- **Tail Arm** (l_h, l_v)
- **Airfoil Section**
- **Aspect Ratio** (AR_h, AR_v)

- **Taper Ratio** (λ_h, λ_v)
- **Span** (b_h, b_v)
- **Root & Tip Chords** (C_{root}, C_{tip})
- **Mean Aerodynamic Chord** (MAC_h, MAC_v)
- **Sweep Angle** (Λ_h, Λ_v) (0 for low-speed RC aircraft)
- **Dihedral/Anhedral Angle** (Γ_h, Γ_v)
- **Incidence Angle** (i_h, i_v)

7.3.2 Sizing the Tail: The Volume Coefficient Method

The most effective starting point for sizing the tail is the **tail volume coefficient**. This dimensionless number is a powerful tool because it captures the relationship between the tail's size and its leverage, relative to the main wing. It essentially represents the tail's stabilizing power. Because these ratios are remarkably consistent across aircraft of similar types, we can use historical data from successful designs as a reliable and logical starting point for our new aircraft.

- **Horizontal Tail Volume Coefficient** (V_{HT}): Represents the tail's power to create a pitching moment. It is defined as:

  $$V_{HT} = \frac{l_{HT} \cdot S_{HT}}{c_{MGC} \cdot S}$$

  A higher value leads to stronger static stability but can make the aircraft less responsive to pitch inputs.

- **Vertical Tail Volume Coefficient** (V_{VT}): Represents the tail's power to create a yawing moment. It is defined as:

  $$V_{VT} = \frac{l_{VT} \cdot S_{VT}}{b \cdot S}$$

7.3.3 Optimizing the Tail Arm for Minimum Drag

The tail volume equations highlight a fundamental design trade-off. For a chosen V_{HT}, we can either have a **long tail arm** (l_{HT}) and a **small tail area** (S_{HT}), or a **short tail arm** and a **large tail area**. Both combinations can produce the same stabilizing moment. The key question is: which combination is better?

The answer lies in minimizing the aircraft's total drag. A longer tail arm requires a longer and heavier fuselage tailboom, which adds skin friction drag and weight. A larger tail area also adds skin friction drag and weight directly. The goal is to find the optimal "sweet spot" for the tail arm that results in the minimum combined drag from both the tailboom and the tail surfaces. This is typically done by minimizing the total **wetted area** of the empennage.

Assuming the aft fuselage can be modeled as a simple cone (a frustum) with a starting radius R_1 and an ending radius R_2, we can derive formulas for the optimal tail arm length.

- **Method 1 (Horizontal Tail Only)**: If we are only concerned with sizing the horizontal tail, the optimal tail arm that minimizes the combined wetted area of the tailboom and the HT is:

  $$l_{HT} = \sqrt{\frac{2 \cdot V_{HT} \cdot S \cdot c_{MGC}}{\pi(R_1 + R_2)}}$$

- **Method 2 (Vertical Tail Only)**: Similarly, if we were only sizing the vertical tail, the optimal arm would be:

$$l_{VT} = \sqrt{\frac{2 \cdot V_{VT} \cdot S \cdot b}{\pi(R_1 + R_2)}}$$

- **Method 3 (Combined HT and VT)**: For a conventional tail where the horizontal and vertical surfaces are located close together, it makes sense to optimize for a single, common tail arm (l_T). This is the most practical method for most RC aircraft designs. The optimal tail arm is found by minimizing the wetted area of the fuselage plus *both* tail surfaces simultaneously:

$$l_T = \sqrt{\frac{2 \cdot S(V_{HT} \cdot c_{MGC} + V_{VT} \cdot b)}{\pi(R_1 + R_2)}}$$

This final equation gives us a powerful analytical tool to determine the best tail arm length based on our initial design choices for the tail volume coefficients and wing geometry. *For more in-depth understanding of tail sizing, refer to Chapter 11.4 in Gudmundsson.*

7.3.4 A Practical, Iterative Design Approach

The tail design is not a one-shot calculation; it is an iterative process of refinement. The formulas above provide a logically derived starting point, which must then be checked and adjusted using more detailed analysis.

1. **Initial Selection**: Choose target values for V_{HT} and V_{VT} from historical data for similar, successful RC aircraft.
2. **Fuselage Approximation**: Model the aft fuselage as a simple cone (frustum) and define its start (R_1) and end (R_2) radii.
3. **Calculate Optimal Tail Arm (l_T)**: Use the combined optimization formula (Method 3) to calculate the initial optimal tail arm length.
4. **Calculate Initial Tail Areas (S_{HT} and S_{VT})**: With the optimal tail arm and the chosen volume coefficients, calculate the required planform area for each tail surface using the rearranged volume coefficient formulas.
5. **Define Full Tail Geometry**: With the areas now known, select appropriate aspect ratios (typically 3-5 for the HT, 1-2 for the VT), taper ratios (often matching the wing), and an airfoil (e.g., NACA 0012) to fully define the 3D shapes of the tail surfaces.
6. **Analyze and Refine (The Iteration Loop)**: This is an important step.
   - Model the entire aircraft—wing, fuselage, and the newly sized tail—in an analysis program like XFLR5. (Note: You will need to enter the weight distribution, parameters apart from just defining the wing + tail setup in XFLR5 before performing the analysis)
   - Perform a stability analysis to calculate the aircraft's **static margin**. The static margin is the most important measure of longitudinal stability; it is the distance between the aircraft's neutral point and its center of gravity, expressed as a percentage of the wing's mean chord.
   - **Check the results**: Is the static margin within the desired range? If not, the tail's effectiveness must be changed.

- **Iterate**:
  - If the static margin is **too low** (e.g., $< 5\%$), the aircraft is not stable enough. To fix this, you must increase the horizontal tail's effectiveness. The most direct way is to increase the V_{HT}. Go back to Step 1, choose a larger V_{HT} (e.g., increase from 0.60 to 0.65), and recalculate the entire sequence.
  - If the static margin is **too high** (e.g., $> 15\%$), the aircraft is overly stable and will feel sluggish and unresponsive to pitch control. To fix this, you must decrease the tail's effectiveness. Go back to Step 1, choose a smaller V_{HT}, and recalculate.

7.4 Tail Configuration

The pros and cons of various tail configurations, such as the conventional, T-tail, and V-tail, are discussed in Section 4.2.8.

7.5 Spin Dynamics and Recovery

7.5.1 What is a Spin?

A spin is an autorotating motion that can occur after a wing stalls. It is not simply a dive; it is a complex flight condition where the aircraft descends in a helical (corkscrew) path at a high angle of attack and low airspeed.

A spin begins with an **asymmetric stall**. If one wing stalls before the other (often during a poorly coordinated turn), the stalled wing loses lift and creates significantly more drag. The still-flying wing continues to produce lift. This imbalance in lift creates a strong rolling motion, and the imbalance in drag creates a strong yawing motion, forcing the aircraft into the characteristic autorotation of a spin.

7.5.2 Spin Recovery Procedure

The standard procedure for spin recovery is often remembered by the acronym **PARE**:

1. **P**ower to Idle: This reduces the effect of the propeller slipstream on the tail and minimizes altitude loss during recovery.

2. **A**ilerons Neutral: Ailerons can be ineffective or even worsen the spin, so they should be neutralized.

3. **R**udder Opposite: Apply full rudder opposite to the direction of rotation. This is the primary control input to stop the yawing motion.

4. **E**levator Forward: Push the control stick forward to lower the aircraft's nose. This reduces the angle of attack, unstalls the wings, and allows the aircraft to regain flying speed.

Once rotation stops, the rudder is neutralized, and the pilot gently pulls back on the elevator to recover from the resulting dive.

7.5.3 Factors Affecting Spin Characteristics

- **Mass Distribution**: The location of mass is critical. A **fuselage-heavy** aircraft (mass concentrated along the centerline) is generally easier to recover from a spin than a **wing-heavy** aircraft (mass distributed along the wingspan). For an RC aircraft, keeping heavy components like batteries and payloads near the CG is beneficial for spin characteristics.

Gudmundsson-Fig11-8.png

Figure 19: The phases of a spin. An asymmetric stall (yaw and wing drop) leads to an incipient spin, which develops into a stabilized spin. The typical recovery procedure is designed to stop the rotation and reduce the angle of attack to recover to normal flight.

- **Tail Configuration**: The tail design is the most important factor in spin recovery. The rudder must have enough authority to stop the rotation. In a **conventional tail** configuration, the turbulent wake from a stalled horizontal tail can "blanket" the vertical tail, rendering the rudder ineffective. This is a primary reason why **T-tails** are often used on aerobatic and trainer aircraft, as they keep the rudder in cleaner air during a spin.

7.5.4 Spin Awareness in the RC Context: The Base-to-Final Turn

The most common scenario for an inadvertent spin is the low-altitude, low-speed turn from the base leg to the final approach for landing. If a pilot tries to tighten the turn with too much rudder (a skidding turn), the inner wing slows down even more, its angle of attack increases, and it can stall abruptly. With insufficient altitude to recover, the result is often catastrophic. This highlights the importance of designing an aircraft with gentle stall characteristics and avoiding low, slow, uncoordinated turns.

Gudmundsson-Fig11-11.png

Figure 20: A common cause of fatal accidents: an uncoordinated, skidding turn at low altitude leads to an asymmetric stall and an incipient spin with no room to recover.

8 Fuselage, Landing Gear, and Propulsion

This chapter covers the design and analysis of the aircraft's core components beyond the lifting surfaces. The fuselage houses the payload and systems, the landing gear provides ground operation capabilities, and the propulsion system generates the thrust needed for flight. Each component must be designed to be lightweight, low-drag, and robust enough to meet the demands of the competition.

8.1 Fuselage Design

The fuselage is the central body of the aircraft. Its primary purpose in an RC competition context is to connect the main components (wing, tail, and landing gear), to house the mission-critical systems (payload, electronics), and to contribute as little as possible to the aircraft's total drag.

8.1.1 Fuselage Shapes for RC Applications

The shape of the fuselage is a trade-off between aerodynamic efficiency (low drag) and ease of manufacturing. While many shapes are possible, they generally fall into three categories.

- **Frustum (Boxy) Fuselage**: This shape is constructed from flat or single-curved panels, often resulting in a square or rectangular cross-section.
  - *Pros*: The main advantage is the **ease and speed of manufacturing**. Using materials like balsa sheets, foam board, or simple composite plates, a strong and lightweight fuselage can be built quickly without complex molds or tooling. This shape also offers the most **efficient use of internal volume**, which is critical for accommodating a bulky, often rectangular, payload.
  - *Cons*: This shape has greater aerodynamic drag compared to more streamlined options.
- **Tubular (Circular/Elliptical) Fuselage**: This shape uses a series of formers (bulkheads) and longerons (stringers) to create a circular or elliptical cross-section, which is then covered by a skin.
  - *Pros*: Offers lower drag than a comparable square cross-section and is structurally efficient. It is a classic and well-understood method for model aircraft construction.
  - *Cons*: Manufacturing is more labor-intensive than a simple box. Fitting a rectangular payload into a circular fuselage is an inefficient use of space, often requiring a larger overall fuselage and thus more wetted area and weight.
- **Tadpole (Streamlined) Fuselage**: This is a highly aerodynamic shape that is wide at the front and tapers to a very thin boom towards the tail.
  - *Pros*: Offers the **lowest possible drag**. This is due to maintaining a laminar boundary layer over a larger portion of the body and having a significantly smaller wetted area in the rear section. The drag of a frustum fuselage can be nearly 50% greater than that of a tadpole shape, which is a substantial aerodynamic advantage.
  - *Cons*: This shape is **very difficult to manufacture** without molds and composite materials. The required compound curves are not feasible with simple sheet materials. Furthermore, the tapered rear section provides almost no usable volume, making it completely impractical for a payload-carrying aircraft. This shape is best suited for gliders or pylon racers, not weightlifters.

RC Aircraft Context: A frustum (boxy) fuselage is often a practical choice for us student teams, as it is easier to manufacture with common materials like wood and foam and is volumetrically efficient for carrying a standardized payload. While a more streamlined tubular or tadpole shape offers lower drag, the manufacturing complexity and inefficient use of payload volume for the tadpole shape are significant drawbacks for many RC designs.

8.1.2 Fineness Ratio

The fuselage **fineness ratio** (FR) is the ratio of its length to its maximum diameter or width. It is a key parameter in determining the fuselage's aerodynamic drag.

$$FR = \frac{l_{fus}}{d_{fus}}$$

where l_{fus} is the fuselage length and d_{fus} is its maximum diameter or width.

For the aft section of the fuselage (the tail cone or empennage section), an ideal fineness ratio is between **3.0 and 3.35 or 6:1 according to Roskam's Aircraft Design** to minimize drag. Aiming for this range in the design of the fuselage section behind the wing will help reduce pressure drag from flow separation.

8.1.3 Fuselage Sizing and Layout Process

The primary goal of the initial fuselage layout is to position all internal components (motor, battery, ESC, servos, payload) such that the aircraft's Center of Gravity (CG) remains within the stable range for all loading conditions. The following six-step process provides a logical workflow to achieve this.

1. **Establish Wing and Tail Geometry**: Begin with a scaled top-view drawing of the wing and horizontal tail planforms, separated by the correct tail arm (l_{HT}) as determined from your stability analysis. This defines the core aerodynamic layout of the aircraft.

2. **Define Target CG Envelope**: On the drawing, mark the desired forward and aft CG limits on the wing's Mean Geometric Chord (MGC). For a conventional RC aircraft, a typical stable range is between **15% and 35% of the MGC**.

3. **Create a Component List**: Create a spreadsheet listing every component that will be inside the fuselage: motor, ESC, battery, receiver, servos, payload, landing gear, etc. Record the weight of each item.

4. **Estimate Component Locations**: In the spreadsheet, assign an initial x-coordinate (longitudinal position) to each component's individual CG, relative to a fixed datum (like the wing's leading edge). Use this to calculate the aircraft's empty-weight CG (X_{CGe}).

   Note: The last 2 steps can also be done on XFLR5

5. **Iterate CG Placement**: Calculate the aircraft's CG for all possible loading scenarios (e.g., empty, full payload, different battery positions if applicable). Using trial and error, shift the components longitudinally in your drawing and spreadsheet until the entire calculated CG range for all flight conditions falls within the target CG envelope defined in Step 2. It is most effective to move the heaviest components, like the battery and payload, to make significant adjustments.

6. **Draw the Fuselage Outline**: Once the internal component layout is finalized and the CG is in the correct location, trace the final fuselage outline (the Outer Mold Line, or OML) around all the components. Ensure there is adequate clearance for all parts, wiring, and the payload bay mechanism.

8.1.4 Refining the External Shape

After the initial layout is complete, consider these refinements:

- **Streamlining**: Ensure the fuselage has smooth transitions, especially in the nose section to minimize stagnation and at the tail cone to prevent flow separation.
- **Tail Upsweep Angle**: The bottom line of the aft fuselage must be angled upwards to provide clearance for rotation during takeoff. As a rule, the aircraft should be able to rotate to its wing's stall angle of attack, or at least **15 degrees nose-up**, without the tail striking the ground.
- **Structural Load Paths**: Be mindful of where major loads are introduced. The bulkheads where the wing spars, landing gear, and firewall are attached must be robust. Avoid placing large cutouts for hatches or payload bays in these high-stress areas without adding proper reinforcement around the opening.

The structural layout of the fuselage is discussed in more detail in Section 5.4.2

8.2 Landing Gear Design

The landing gear must be robust enough to withstand repeated landings and rough ground operations while being as lightweight as possible. For most RC applications, a simple, fixed landing gear is the most practical choice, as the drag penalty is minimal at lower speeds compared to the significant weight and complexity of a retractable system.

8.2.1 Landing Gear Arrangements

The arrangement of the wheels relative to the center of gravity (CG) is the most critical design choice for the landing gear.

- **Tricycle Gear (Nosewheel + Two Main Wheels Aft of CG)**:
  - *Pros*: Inherently stable on the ground because the CG is forward of the main wheels, making it highly resistant to swerving or ground looping. The level fuselage attitude on the ground can simplify payload loading and ground handling.
  - *Cons*: The nose gear strut and wheel can add weight and drag compared to a simple tailwheel. The main gear must be placed carefully to allow for sufficient nose-up rotation during takeoff without the tail striking the ground.
  - *RC Aircraft Context*: This is the most common configuration for RC aircraft, especially for payload lifters. Its stability makes takeoff and landing runs more predictable and safer.
- **Taildragger (Two Main Wheels Forward of CG + Tailwheel/Skid)**:
  - *Pros*: Generally lighter and produces less aerodynamic drag than a tricycle gear. It naturally provides excellent propeller clearance. The nose-high ground attitude allows the wing to be held at a high angle of attack, which can aid in generating high lift for shorter takeoffs from rough surfaces.
  - *Cons*: Inherently unstable on the ground; if the aircraft swerves, the CG's location behind the main wheels will cause the turn to tighten, a behavior which can easily lead to a damaging ground loop.
  - *RC Aircraft Context*: A viable option for designs aiming to maximize short-field takeoff performance and minimize weight/drag. However, its ground instability requires more careful control during the takeoff run and landing rollout.

- **Bicycle or Tandem Gear (Two Main Wheels Fore and Aft of CG + Outriggers)**:
  - *Pros*: Useful for aircraft with long, narrow fuselages where a wide main gear track is impractical.
  - *Cons*: This arrangement requires the aircraft to take off and land in a flat attitude, as the aft wheel prevents significant rotation. This is a major drawback for a high-lift aircraft that needs to achieve a high angle of attack for takeoff. The outrigger wheels on the wings add complexity and weight.
  - *RC Aircraft Context*: Rarely used for payload-lifting aircraft. It is more suited for unconventional designs like high-aspect-ratio powered gliders, where the fuselage is too narrow for other gear types.

8.2.2 Types of Landing Gear Legs and Shock Absorbers

The method of shock absorption is key to the landing gear's durability. While complex oleo-pneumatic struts are common on full-scale aircraft, simpler and lighter methods are better suited for RC applications.

- **Solid Spring Gear**: This type uses a flexible strut, typically made from a single piece of bent aluminum, steel wire, or a composite leaf spring. It is extremely simple, robust, low-cost, and reliable. Its main drawback is that it has very little natural damping, which can lead to bouncing or oscillation on rough ground.

- **Trailing Link / Levered Gear**: This design uses a pivot point to allow the wheel to swing backward and upward when hitting a bump. The shock is absorbed by a separate spring or elastic element. This provides a mechanically superior way to handle bumps compared to a rigid strut and is an excellent choice for rough-field operations.

- **Tires as Shock Absorbers**: The tires themselves are a primary source of shock absorption. Using large, pneumatic (air-filled) tires with low pressure is one of the simplest and most effective ways to improve ground handling on imperfect surfaces and absorb landing energy.

Figure 21: Common types of landing gear legs and shock absorbers suitable for RC aircraft.

8.2.3 Geometric Layout

Once a landing gear configuration is selected, a detailed geometric layout must be performed to ensure stability and proper function. This process involves positioning the wheels relative to the Center of Gravity (CG) to satisfy requirements for takeoff rotation, tail clearance, and ground stability. For a detailed, step-by-step guide on how to perform this layout for the different gear configurations, please refer to Section 13.3 in Gudmundsson. Other things to keep in mind while designing the landing gear are:

- **Ground Clearance**: The landing gear must be long enough to provide adequate clearance.
  - **Propeller Clearance**: The distance between the propeller tip and the ground should be at least 2-3 inches.
  - **Tail Clearance**: The aircraft must be able to rotate to its takeoff angle of attack (typically 10-15 degrees) without the tail striking the runway.

- **Tip-Over Angles**: These angles determine the stability of the aircraft on the ground. They are calculated using simple trigonometry based on the CG height, wheelbase, and wheel track.
  - **Longitudinal Tip-Over Angle**: This is the angle the aircraft can be tilted forward before it noses over. For a tricycle gear, the main wheels should be placed a sufficient distance aft of the CG to ensure this angle is greater than **15 degrees**.
  - **Lateral Tip-Over Angle**: This is the angle the aircraft can be tilted sideways before a wingtip strikes the ground. A wider wheel track increases this angle. A value greater than **55 degrees** is generally considered safe.

8.2.4 Landing Gear Loads and Dynamics

The landing gear must be designed to withstand the kinetic energy of touchdown. The severity of this impact is determined by the aircraft's vertical speed, or **sink rate** (w), at the moment the wheels make contact. The average deceleration (a_z) the gear must provide is a function of this sink rate and the available shock absorber travel distance (d).

$$a_z = -\frac{w^2}{2d}$$

For a more detailed analysis, a landing gear strut can be modeled as a simple **mass-spring-damper** system, as illustrated in Figure 22.

Landing_Gear_Dynamics.jpeg

Figure 22: Idealizing the landing gear as a simple mass-spring-damper dynamic system.

This system is governed by a second-order ordinary differential equation, known as an Equation of Motion (EOM):

$$m\ddot{z} + c\dot{z} + kz = 0$$

where:

- m is the mass supported by the landing gear.
- k is the spring stiffness of the shock absorber.
- c is the damping coefficient provided by the shock absorber.
- z, $\dot{z}$, and $\ddot{z}$ are the vertical displacement, velocity, and acceleration of the aircraft mass, respectively.

The solution to this EOM describes the aircraft's vertical motion after touchdown. For a typical underdamped system ($c < 2\sqrt{km}$), the displacement, velocity, and acceleration are described by the following equations:

$$z(t) = e^{-\frac{c}{2m}t}[C_1 \cos(\omega t) + C_2 \sin(\omega t)] \tag{1}$$

$$\dot{z}(t) = \left(\frac{c}{2m}\right) e^{-\frac{c}{2m}t}[\omega C_1 \cos(\omega t) - \omega C_2 \sin(\omega t)] \tag{2}$$

$$\ddot{z}(t) = \left(-\frac{c^2\omega^2}{4m^2}\right) e^{-\frac{c}{2m}t}[C_1 \cos(\omega t) + C_2 \sin(\omega t)] \tag{3}$$

where $\omega = \frac{1}{2m}\sqrt{4(k/m) - (c/m)^2}$ is the damped natural frequency, and C_1 and C_2 are constants determined by the initial conditions at touchdown (i.e., initial displacement is zero, and initial velocity is the sink rate w). This analysis allows an engineer to predict the peak loads and deflections the landing gear will experience.

8.3 Propulsion System: Propeller Modeling

While various propeller types exist, this section will focus on the **fixed-pitch propeller**. Due to their simplicity, low cost, and robustness, they are a practical choice for many RC aircraft projects where design constraints and budget are primary considerations.

8.3.1 Propeller Geometry and Terminology

The performance of a propeller is intrinsically linked to its geometry. A propeller blade functions as a rotating airfoil, generating aerodynamic forces. For a more detailed exploration of these topics, refer to Gudmundsson, Chapter 15.

- **Diameter (D_p)**: The distance from tip to tip. This is a primary factor in how much air the propeller can engage and is critical for thrust production.
- **Geometric Pitch Angle (β)**: The angle of the blade's chord line with respect to the plane of rotation. This angle is twisted along the blade's length. The theoretical forward distance the propeller would move in one revolution, the **Geometric Pitch (P_G)**, is related to this angle at any radial station, r:

$$P_G = 2\pi r \tan\beta \qquad \Longrightarrow \qquad \beta = \tan^{-1}\left(\frac{P_G}{2\pi r}\right)$$

  Propeller pitch is typically defined by its value at the 75% radius station (β_G).

$$\beta_G = \tan^{-1}\left(\frac{4P_G}{3\pi D_p}\right)$$

- **Helix Angle (ϕ)**: The angle of the actual path the blade travels through the air, resulting from the combination of the aircraft's forward speed (V_∞) and the blade's rotational speed (Ωr).

$$\tan\phi = \frac{V_\infty}{\Omega r} = \frac{V_\infty}{2\pi r n} = \frac{30V_\infty}{\pi r \cdot RPM}$$

- **Angle of Attack (α)**: The angle between the blade's chord line and the incoming air. This is the angle that generates the aerodynamic force. It is the difference between the geometric pitch angle and the effective helix angle, which is modified by the induced velocity (w)—the acceleration of air through the propeller disc.

$$\alpha = \beta - \tan^{-1}\left(\frac{V_\infty + w}{\Omega r}\right)$$

8.3.2 Propeller Speed

The speed of the blade elements varies along the radius and is a critical factor in performance, especially near the tips where compressibility can become an issue.

- **Rotational Speed (V_{ROT})**: The tangential speed of a blade element at radius r.

$$V_{ROT} = \Omega r$$

- **Resultant Speed (V_R)**: The speed of the blade element relative to the surrounding air, combining forward and rotational motion (but not including induced velocity).

$$V_R = \sqrt{V_\infty^2 + V_{ROT}^2} = \sqrt{V_\infty^2 + (\Omega r)^2}$$

- **Tip Speed (V_{tip})**: The resultant speed at the propeller tip ($r = R_p = D_p/2$). This is the maximum speed experienced by any part of the blade.

$$V_{tip} = \sqrt{V_\infty^2 + (\pi n D_p)^2} = \sqrt{V_\infty^2 + \left(\frac{\pi \cdot RPM \cdot D_p}{60}\right)^2}$$

- **Tip Mach Number (M_{tip})**: The ratio of the tip speed to the local speed of sound (a). To avoid significant efficiency losses and excessive noise from shock wave formation, this value should be kept below approximately 0.75-0.80.

$$M_{tip} = \frac{V_{tip}}{a}$$

8.3.3 Propeller Aerodynamic Effects on the Airframe

A propeller does more than just produce forward thrust; it creates a complex, swirling flowfield and induces several forces and moments on the aircraft that must be accounted for in the design.

Figure 23: Key aerodynamic effects from a propeller: A) Asymmetric thrust (P-Factor) at an angle of attack, creating a yawing moment. B) Rotational propwash (swirl) inducing a rolling moment.

- **Propwash**: This is the accelerated, rotating column of air (slipstream) that flows rearward from the propeller.
  - *Increased Dynamic Pressure*: Surfaces located within the propwash (such as the wing root and empennage) experience a higher airspeed than the freestream. This makes control surfaces like the rudder and elevator more effective at low speeds but also increases the parasite drag on those components.
  - *Swirl*: The air in the propwash rotates in the same direction as the propeller. This swirling flow strikes the vertical tail on one side, creating a sideways aerodynamic force and a resulting yawing moment on the aircraft.
- **Torque**: In accordance with Newton's Third Law, the motor's action of turning the propeller in one direction (e.g., clockwise when viewed from behind) results in an equal and opposite reaction, causing the entire airframe to want to roll in the opposite direction (counter-clockwise). This effect is most pronounced at high power settings and low airspeeds, such as during the takeoff run.

- **Asymmetric Blade Thrust (P-Factor)**: When the aircraft is flying at a positive angle of attack, the propeller's plane of rotation is tilted relative to the oncoming airflow. This causes the downward-moving blade to have a higher angle of attack—and thus generate more thrust—than the upward-moving blade. For a clockwise-rotating propeller, this results in the center of thrust shifting to the right of the propeller hub, creating a yawing moment to the left.
- **Gyroscopic Precession**: The spinning propeller behaves like a gyroscope. When a moment is applied to one axis, it results in a secondary moment about an axis 90 degrees later in the direction of rotation. For example, if the pilot pitches the aircraft's nose up (a yawing motion of the propeller disk), the propeller will precess, creating a yawing moment on the aircraft. This effect is most noticeable in taildragger aircraft when the tail is raised during takeoff.

Propeller Normal and Side Forces When the propeller disc is inclined to the incoming flow, either from the aircraft's angle of attack or a sideslip, a net aerodynamic force is produced perpendicular to the propeller's axis of rotation.

Figure 24: Generation of a propeller Normal Force (F_N) at an angle of attack (α). The downward moving blade generates more lift, creating a net upward force and a nose-up pitching moment for a tractor configuration.

- **Normal Force (F_N)**: During flight at a positive angle of attack, the asymmetric loading on the blades produces a net force acting upwards, perpendicular to the thrust axis. For a tractor configuration where the propeller is ahead of the CG, this normal force creates a destabilizing nose-up pitching moment. In a pusher configuration where the prop is behind the CG, this same force would create a stabilizing nose-down moment.
- **Side Force (F_S)**: A similar effect occurs when the aircraft is in a yawed condition (sideslip). A net force is generated in the sideways direction. For a tractor configuration, this side force is destabilizing, creating a moment that tends to increase the yaw angle, which must be counteracted by the rudder.

8.3.4 Propeller Performance and Thrust Estimation

Estimating propeller thrust is essential for performance analysis. The most accurate method is to use data provided directly by the manufacturer, often in the form of a performance map or table.

Figure 25: An example of a propeller efficiency map provided by a manufacturer. Efficiency (η_p) is found at the intersection of the Advance Ratio (J) and the Power Coefficient (C_p).

Method 1: Using a Manufacturer Efficiency Table If a performance table like the one in Figure 25 is available, the thrust can be determined with the following steps:

1. **Calculate Advance Ratio (J)** for the given flight condition (airspeed V_∞ and rotational speed n).

$$J = \frac{V_\infty}{nD_p}$$

2. **Calculate Power Coefficient (C_P)** for the given motor power (P), air density (ρ), and rotational speed (n).
$$C_P = \frac{P}{\rho n^3 D_p^5}$$
3. **Find Propeller Efficiency (η_p)** from the table by finding the intersection of the calculated J (row) and C_P (column). Interpolation between values may be necessary.
4. **Calculate Thrust (T)** using the fundamental thrust-power relationship:
$$T = \frac{\eta_p P}{V_\infty}$$
(Ensure consistent units, e.g., P in ft-lb/s, V_∞ in ft/s, T in lb).

Method 2: Estimation Without Manufacturer Data If a performance table is not available, an engineering approximation of the thrust curve for a fixed-pitch propeller can be generated. For a detailed guide on this quadratic interpolation method, which uses static thrust and an estimated optimal performance point to build the curve, refer to Section 15.4.3 in Gudmundsson.

8.3.5 Fundamental Propeller Thrust (Momentum Theory)

While the previous methods are practical for estimation, the Rankine-Froude Momentum Theory provides the fundamental physics behind thrust generation. It models the propeller as an "actuator disc" that adds energy to the air passing through it. While not typically used for direct thrust calculation in a design project, its concepts are essential for a deeper understanding.

Figure 26: Idealized flow model for the Rankine-Froude Momentum Theory, showing the streamtube of air passing through the actuator disc.

The key results from this theory are:

- **Induced Velocity (w)**: The theory shows that the air is accelerated as it approaches the propeller. The velocity exactly at the propeller disc (V_2) is the average of the freestream velocity (V_∞) and the final velocity in the far wake (V_3). The added velocity at the disc is the induced velocity, w.
$$V_2 = V_\infty + w$$
The induced velocity can be calculated if the thrust is known:
$$w = \frac{1}{2}\left[-V_\infty + \sqrt{V_\infty^2 + \frac{2T}{\rho A_p}}\right]$$
- **Thrust**: Thrust is the product of the mass flow rate of air ($\dot{m}$) and the total change in velocity ($V_3 - V_\infty = 2w$).
$$T = \dot{m}(2w) = \left[\rho A_p (V_\infty + w)\right](2w)$$
- **Ideal (Froude) Efficiency (η_i)**: The theory provides the absolute maximum possible efficiency for any propeller, which is achieved when no energy is lost to blade drag or swirl. It shows that efficiency is lost by leaving kinetic energy in the wake.
$$\eta_i = \frac{\text{Useful Power}}{\text{Total Power}} = \frac{T V_\infty}{T(V_\infty + w)} = \frac{1}{1 + (w/V_\infty)}$$

This elegantly demonstrates that for a given thrust, a smaller induced velocity (w) results in higher ideal efficiency. This is achieved by using a larger diameter propeller (A_p) to act on a larger mass of air.

9 Performance Analysis

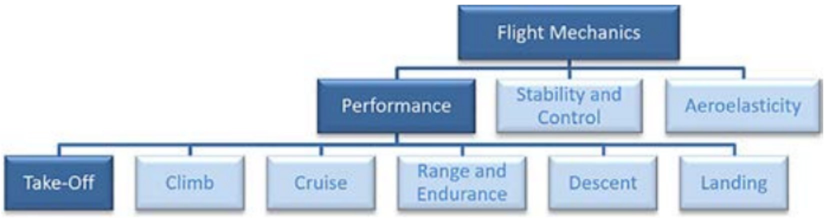


Figure 27: An organizational map placing performance theory among other the disciplines of Flight Mechanics (Source:

Performance analysis is the process of predicting how the aircraft will fly. It answers critical questions: How fast will it go? How quickly will it take off? How much weight can it carry? The foundation of all performance analysis is a reliable understanding of the aerodynamic forces acting on the aircraft, primarily lift and drag. This chapter focuses on the methods to estimate these forces.

9.1 Aircraft Drag Analysis

Drag is the aerodynamic force that resists the aircraft's motion through the air. A thorough and realistic estimation of drag is arguably the most important analysis a design team will perform. An underestimation will lead to an aircraft that fails to meet its takeoff and flight requirements, while a significant overestimation may lead to an unnecessarily oversized and heavy design.

9.1.1 Types of Drag in Low-Speed Flight

Total aircraft drag is the sum of several distinct components. For a subsonic RC aircraft, the following types are the most important to understand. Note that effects like wave drag (associated with supersonic shock waves) and ram drag (associated with jet engine inlets) are not relevant in this flight regime.

- **Skin Friction Drag**: This drag is generated by the viscous shearing stress as air flows over the "wetted" surface of the aircraft. Its magnitude depends heavily on whether the boundary layer flow is smooth (laminar) or chaotic (turbulent), and on the total surface area of the aircraft.
- **Pressure Drag (Form Drag)**: This drag is caused by the distribution of pressure acting on a body's surface. It is highly dependent on the shape of the object. On a streamlined body, the flow may separate from the aft surface, creating a low-pressure wake that pulls the aircraft backward. On a bluff body like landing gear, the high pressure on the front and low pressure in the wake are the dominant sources of drag.
- **Interference Drag**: When two components are joined (like a wing and a fuselage), their flow fields interact, often causing additional separation and drag. The total drag of the combination is typically greater than the sum of the individual parts when measured in isolation.
- **Drag-due-to-Lift**: This is the drag that is inherently created as a byproduct of generating lift. It has two main components:

– **Inviscid Drag-due-to-Lift (Induced Drag)**: As a finite wing generates lift, it creates vortices at the wingtips. The energy required to create these vortices is drawn from the aircraft, resulting in a drag force. This is the dominant form of drag at low speeds and high lift coefficients.

– **Viscous Drag-due-to-Lift**: As an airfoil's angle of attack increases to generate more lift, the pressure distribution changes and flow separation can begin to increase, adding to the profile drag. This is the viscous component of the drag associated with creating lift.

- **Trim Drag**: This is an induced drag penalty that arises from the need to trim the aircraft for stable flight. Typically, the horizontal tail must generate a small amount of lift (often downwards) to balance the pitching moment from the wing, which creates its own induced drag.

9.1.2 The Drag Polar Model

The relationship between an aircraft's lift and drag is represented by a curve called the **drag polar**, which is a plot of the lift coefficient (C_L) versus the drag coefficient (C_D) for various angles of attack.

Drag_Polar_Example.jpg

Figure 28: A typical drag polar for a cambered aircraft. The minimum drag ($C_{D_{min}}$) occurs at a positive lift coefficient. The maximum lift-to-drag ratio (L/D_{max}) is found at the point where a line from the origin is tangent to the curve.

For performance calculations, this relationship is typically modeled with a parabolic equation. The following three-term model is comprehensive and well-suited for aircraft with cambered airfoils:

$$C_D = C_{D_{min}} + K'C_L^2 + K''(C_L - C_{L_{min}})^2$$

A common term used in aerodynamics is the **drag count**, which is simply the drag coefficient multiplied by 10,000. For example, a C_D of 0.0275 is equal to 275 drag counts.

9.1.3 Component Buildup Method for Estimating $C_{D_{min}}$

The most practical way to estimate the aircraft's minimum parasite drag ($C_{D_{min}}$) is to calculate the drag of each individual component and then sum them together. The total $C_{D_{min}}$ is given by:

$$C_{D_{min}} = \frac{1}{S_{ref}} \sum (C_f \cdot FF \cdot Q \cdot S_{wet})_{\text{comp}} + \Delta C_{D_{misc}}$$

The contribution of each component is found by estimating its skin friction (C_f), form factor (FF), interference factor (Q), wetted area (S_{wet}) which is the surface of the component in contact with air and reference area (S_{ref}) is the wing area.

Wing Drag

- **Skin Friction Coefficient (C_f)**: Determined by the Reynolds Number ($Re = \rho V L/\mu$) of the wing, calculated using the Mean Aerodynamic Chord (MAC) as the characteristic length L. For RC aircraft, a conservative approach is to assume the flow is turbulent. The turbulent skin friction coefficient is calculated as:

$$C_f = \frac{0.455}{(\log_{10} Re)^{2.58}}$$

- **Form Factor (FF)**: Accounts for the pressure drag due to the wing's thickness.

$$FF = 1 + L(t/c) + 100(t/c)^4$$

  where (t/c) is the wing's thickness-to-chord ratio. The parameter L depends on the chordwise position of the airfoil's maximum thickness, $(x/c)_{max}$:

  - $L = 1.2$ for $(x/c)_{max} \geq 0.3$ (typical for conventional airfoils)
  - $L = 2.0$ for $(x/c)_{max} < 0.3$ (typical for older laminar-flow airfoils)

- **Interference Factor (Q)**: Accounts for the wing-fuselage junction. Use $Q = 1.0$ for a well-faired high or mid-wing, and $Q = 1.1 - 1.4$ for a low wing.

- **Wetted Area (S_{wet})**: Approximated as $S_{wet} \approx 2.02 \times S_{exposed}$, where $S_{exposed}$ is the planform area of the wing not covered by the fuselage.

Fuselage Drag

- C_f: Calculated using the Reynolds number based on the total fuselage length (l_f).

- FF: The form factor for a fuselage depends on its fineness ratio ($f = l_f/d_f$, where d_f is the effective diameter).

$$FF = 1 + \frac{60}{f^3} + \frac{f}{400}$$

- Q: The interference factor for the fuselage itself is 1.0.

- S_{wet}: The wetted area of the fuselage should be calculated from the geometry of the design, often using CAD software.

Empennage Drag The drag of the horizontal and vertical tails is calculated exactly like the wing, using their own respective areas, MACs, Reynolds numbers, and thickness ratios. A typical interference factor for tail surfaces with the fuselage is $Q \approx 1.05$.

Landing Gear Drag The drag from a fixed landing gear is a major component of the total parasite drag and is primarily caused by pressure drag from its bluff components. A detailed drag estimation involves calculating the drag of each part (wheels, struts, fairings) and summing their contributions. The total drag coefficient contribution for the landing gear is given by:

$$\Delta C_{D_{gear}} = \frac{1}{S_{ref}} \sum (C_{D_S} \cdot A_S)_{comp}$$

where C_{D_S} is the source drag coefficient of a component based on its own reference area A_S (typically the frontal area).

- **Tires and Wheels**: The drag of an unfaired tire is significant. The source drag coefficient (C_{D_S}) depends on the tire's shape.
  - For a standard RC aircraft tire, check Table 16-15 of Gudmundsson for a representative value is C_{D_S}.
  - The reference area is the tire's frontal area: $A_S = d \times w$, where d is the tire diameter and w is its width.
- **Struts**: The drag of the supporting struts depends on their cross-sectional shape.
  - For a simple round wire or tube strut, $C_{D_S} \approx 1.0$.
  - For a streamlined (airfoil-shaped) strut or fairing, $C_{D_S} \approx 0.3$.
  - The reference area A_S is the strut's frontal area (length $\times$ thickness).
- **Wheel Pants/Fairings**: Using wheel pants (fairings) is a highly effective way to reduce overall landing gear drag. A well-designed fairing that fully encloses the wheel and strut intersection (like Type A3 in Figure 16-58 of Gudmundsson) can have a combined C_{D_S} as low as 0.05 based on its own frontal area.

This process would be repeated for all the gear legs (3 if it were a tail dragger or tricycle), and the results summed to find the total $\Delta C_{D_{gear}}$.

Miscellaneous Drag ($\Delta C_{D_{misc}}$) This term accounts for the drag from small items not included in the main component buildup, such as control horns, hinges, gaps, and antennas. A reasonable initial estimate for these items is about 5 to 10% of $C_{D_{0,components}}$.

9.1.4 Drag-due-to-Lift Calculation

Induced Drag (K') The induced drag factor, K', is calculated using the wing's aspect ratio and its Oswald's efficiency factor, e.

$$K' = \frac{1}{\pi e AR}$$

Oswald's efficiency factor, e, which accounts for the deviation from an ideal elliptical lift distribution, can be assumed between $0.7 < e < 0.85$ or estimated using the formula:

$$e = 0.98(1 - (\frac{d}{b})^2)$$

where d = fuselage diameter and b = wing span.

Viscous Drag due to Lift (K'') This factor is best determined from 2D airfoil data for the chosen airfoil. It can be found by plotting the airfoil's section drag (C_d) against the term $(C_l - C_{L_{min}})^2$. The slope of the linear portion of this curve is the viscous drag factor, K''. For a typical high-lift airfoil used in RC applications, such as the Selig S1223, a value of $K'' \approx 0.0133$ is representative.

Viscous_Drag_Factor_Plot.jpeg

Figure 29: The viscous drag-due-to-lift factor (K'') is the slope of the line when plotting section drag coefficient versus the squared difference from the lift coefficient for minimum drag.