Jet Engine Performance Estimator Project Report

1. Introduction

This project delivers a Python-based tool designed to estimate the performance of various jet engine types, including **Turbojet, Turbofan (High and Low Bypass), Turboprop, and Ramjet engines**. The estimations are rooted in **ideal cycle analysis** and incorporate component isentropic efficiencies for a more realistic, yet simplified, approach. This interactive tool allows users to explore the fundamental thermodynamic principles governing aircraft propulsion systems.

2. Theoretical Basis: Ideal Cycle Analysis

The project's calculations are founded on the **Brayton cycle** (for turbojets, turbofans, and turboprops) and the **Ramjet cycle**, which are idealized thermodynamic cycles representing the operation of these engines.

General Assumptions for Ideal Cycle Analysis:

- **Ideal Gas Behavior:** Air and combustion products are treated as ideal gases with constant specific heats.
  - Ratio of specific heats (gamma): 1.4
  - Specific heat at constant pressure (Cp): 1005 J/kg/K
  - Gas constant for air (R): 287 J/kg/K
- **Isentropic Components (Ideal by Default):** Diffusers, compressors, turbines, fans, and nozzles are assumed to operate isentropically (100% efficient) unless a specific isentropic efficiency (eta) is provided.
- **Constant Pressure Combustion:** Heat addition in the combustor is assumed to occur at constant total pressure.
- **Negligible Fuel Mass:** The mass of fuel added is considered negligible compared to the air mass flow.

- **Full Expansion:** Nozzles are assumed to expand the exhaust gases fully to ambient pressure.

Key Formulas Used:

a. Isentropic Relations:

These relations are fundamental for calculating temperature and pressure changes across components assuming ideal (isentropic) compression or expansion.

- Isentropic Temperature Ratio:
  Tout / Tin = (Pout / Pin)^((gamma-1) / gamma)
- Isentropic Pressure Ratio:
  Pout / Pin = (Tout / Tin)^(gamma / (gamma-1))

b. Component Efficiencies:

Actual performance deviates from ideal due to irreversibilities. Isentropic efficiencies account for this:

- Diffuser Isentropic Efficiency (eta_d):
  eta_d = (Tt2,ideal - T0) / (Tt2,actual - T0) OR eta_d = (Pt2,actual - P0) / (Pt2,ideal - P0)
  (The code uses a simplified form for total pressure recovery based on efficiency)
- Compressor/Fan Isentropic Efficiency (eta_c, eta_f):
  eta_c = (Tt3,ideal - Tt2) / (Tt3,actual - Tt2)
- Turbine Isentropic Efficiency (eta_t):
  eta_t = (Tt4 - Tt5,actual) / (Tt4 - Tt5,ideal)
- Nozzle Isentropic Efficiency (eta_n):
  eta_n = (ht7 - h9,actual) / (ht7 - h9,ideal) OR eta_n = (Ve,actual^2 / 2) / (Ve,ideal^2 / 2)
  (The code uses temperature drop for velocity calculation)

c. Energy Balance & Fuel-Air Ratio:

- Fuel-Air Ratio (f):
  f = (Cp * (Tt4 - Tt3)) / (Q_HV - Cp * Tt4)
  Where Q_HV is the heating value of the fuel.

d. Thrust and Specific Fuel Consumption (TSFC):

- Net Thrust per Unit Air Mass Flow (F_net / m_dot_a):
  F_net / m_dot_a = (1+f) * Ve - V0
  Where Ve is the exhaust velocity and V0 is the flight velocity.
- Thrust Specific Fuel Consumption (TSFC):
  TSFC = m_dot_f / F_net = f / (F_net / m_dot_a)

Specific Engine Cycle Models:

i. Turbojet Engine:

- **Cycle:** Diffuser --> Compressor --> Combustor --> Turbine --> Nozzle.
- Work Balance: Turbine work output equals compressor work input (Wt = Wc).
  Cp * (Tt4 - Tt5) = Cp * (Tt3 - Tt2)

ii. Turbofan Engine:

- **Cycle:** Diffuser --> Fan (splits flow) --> (Core: Compressor --> Combustor --> Turbine --> Core Nozzle) + (Bypass: Bypass Nozzle).
- Work Balance: The turbine provides work for both the core compressor and the fan.
  W_turbine = W_compressor + BPR * W_fan
  Where BPR is the Bypass Ratio.
- **Thrust Contribution:** Total thrust is the sum of core thrust and bypass thrust.

iii. Turboprop Engine:

- **Cycle:** Diffuser --> Compressor --> Combustor --> Turbine (Power Turbine) --> Nozzle.

- Work Balance: The turbine extracts more work than needed for the compressor. The excess work is converted into shaft power to drive a propeller.
  W_shaft = W_turbine - W_compressor
- Thrust Contribution: Primarily from the propeller, with a small residual jet thrust from the exhaust nozzle.
  F_propeller = (W_shaft * eta_prop) / V0

iv. Ramjet Engine:

- **Cycle:** Diffuser --> Combustor --> Nozzle.
- **Operation:** Relies solely on ram compression due to high flight speed; it has no rotating machinery (compressor or turbine).
- **Requirement:** Requires supersonic flight speeds to operate efficiently.

3. Project Features

The Python script offers the following capabilities:

- **Multi-Engine Simulation:** Allows users to select and analyze Turbojet, Turbofan (high and low bypass), Turboprop, and Ramjet engines.
- **Detailed Parameter Input:** Prompts for key operational parameters such as flight Mach number, ambient conditions, pressure ratios, turbine inlet temperature, and bypass ratio.
- **Component Efficiency Inclusion:** Enables the input of isentropic efficiencies for individual components (diffuser, compressor, turbine, fan, nozzle) to simulate non-ideal performance.
- **Clear Performance Output:** Displays calculated net thrust per unit air mass flow and thrust specific fuel consumption (TSFC) in standard units.
- **User-Friendly Interface:** Provides a simple command-line menu for navigation

and input.

- **Input Validation:** Basic validation ensures numerical inputs are within expected ranges.

4. Key Variables and Functions

Functions:

- CALCULATE_ISENTROPIC_TEMPERATURE_RATIO(PRESSURE_RATIO, GAMMA): Helper for isentropic temperature calculation.
- CALCULATE_ISENTROPIC_PRESSURE_RATIO(TEMPERATURE_RATIO, GAMMA): Helper for isentropic pressure calculation.
- ESTIMATE_TURBOJET_PERFORMANCE(...): Calculates performance for a turbojet engine.
- ESTIMATE_TURBOFAN_PERFORMANCE(...): Calculates performance for a turbofan engine.
- ESTIMATE_TURBOPROP_PERFORMANCE(...): Calculates performance for a turboprop engine.
- ESTIMATE_RAMJET_PERFORMANCE(...): Calculates performance for a ramjet engine.
- GET_FLOAT_INPUT(PROMPT, MIN_VAL, MAX_VAL): Utility function for robust user input.
- RUN_ENGINE_ESTIMATOR(): The main function controlling the interactive user interface and calling the appropriate engine estimation functions.

Key Variables (Examples):

- GAMMA_AIR: Ratio of specific heats for air.
- CP_AIR: Specific heat at constant pressure for air.
- HEATING_VALUE_FUEL: Calorific value of the fuel.
- FLIGHT_MACH_NUMBER: Aircraft's Mach number.

- AMBIENT_TEMPERATURE_K, AMBIENT_PRESSURE_PA: Atmospheric conditions.
- COMPRESSOR_PRESSURE_RATIO: Pressure ratio across the compressor.
- TURBINE_INLET_TEMPERATURE_K: Maximum cycle temperature.
- BYPASS_RATIO: Ratio of bypass air mass flow to core air mass flow (for turbofans).
- FUEL_AIR_RATIO: Mass ratio of fuel to air.
- NET_THRUST_PER_UNIT_MASS_FLOW: Calculated net thrust.
- SPECIFIC_FUEL_CONSUMPTION: Calculated fuel efficiency.

5. Limitations of the Project

While this project is an excellent educational tool, it's vital to acknowledge its limitations:

- **Ideal Cycle Simplifications:** The core limitation stems from using ideal cycle analysis. Real engines experience:
  - **Pressure Losses:** Pressure drops in the diffuser, combustor, and nozzle are not fully accounted for (only through component efficiencies for the overall effect, not detailed losses).
  - **Variable Specific Heats:** Specific heats of air and combustion products vary with temperature, which is ignored.
  - **Non-Uniform Flow:** Assumes one-dimensional, uniform flow.
  - **Combustion Efficiency:** Assumes 100% combustion efficiency.
- **Component Interactions:** The model simplifies complex interactions between components (e.g., turbine cooling air, bleed air).
- **Off-Design Performance:** This model primarily focuses on design-point performance and does not accurately predict off-design behavior.
- **Thrust/Power at Zero Flight Speed (Static):** Some formulas, particularly for turboprops, become undefined or less accurate at zero flight velocity. The code includes warnings for these cases.

- **No Mechanical Losses:** Mechanical efficiencies for shafts and gearboxes are not explicitly modeled (except for propeller efficiency).
- **Simplified Turboprop Model:** The turboprop model assumes the turbine expands to ambient pressure to maximize shaft work, which is an idealization.

6. Conclusion

This Jet Engine Performance Estimator provides a robust and accessible platform for understanding the fundamental thermodynamic cycles of various aircraft propulsion systems. By allowing users to manipulate key parameters and component efficiencies, it offers valuable insights into how these factors influence engine thrust and fuel consumption. Despite its inherent simplifications due to ideal cycle analysis, it serves as a strong foundation for further exploration into gas turbine engine performance and design.