AE 481 Team 01 Assignment 4

September 21, 2025

1 Sizing

Initial of the aircraft thrust to weight ratio (T/W) and wing loading (W/S) was analyzed using constraints derived from the competition request for proposal (RFP). The equations used and the rationale for each constraint is explained in this section. Since T/W and W/S must be in terms of takeoff weight, weight fraction corrections are applied. Mission segment weight fractions are determined using the weight sizing code from Assignment 2. The corrections for T/W and W/S are shown in Eq. (1) and Eq. (2), which are derived from Martins [1].

$$\left(\frac{T}{W}\right)_0 = \left(\frac{T_i}{W_i}\right)\left(\frac{W_i}{W_0}\right)\left(\frac{T_i}{T_0}\right)^{-1} \tag{1}$$

$$\left(\frac{W}{S}\right)_0 = \left(\frac{W_i}{S}\right)\left(\frac{W_i}{W_0}\right)^{-1} \tag{2}$$

where the subscript "0" indicates takeoff values. The subscript i represents the weight fraction at the beginning of a mission segment. The ratio T_i/T_0 is the thrust lapse for a specified flight condition. Constraint equations will input and output W_i/S and T_i/W_i which must be converted to and from takeoff values.

1.1 Thrust Lapse

A model from Mattingly [2] was used for engine thrust lapse of low bypass ratio turbofans. All candidate engines from Assignment 1 were categorized as such using data from Nicolai [3].

$$\theta = T/T_{\text{std}} \quad \text{and} \quad \theta_0 = \theta\left(1 + \frac{\gamma-1}{2}M^2\right)$$

$$\delta = P/P_{\text{std}} \quad \text{and} \quad \delta_0 = \delta\left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$\text{Maximum:} \begin{cases} \alpha = \delta_0, & \theta_0 \leq TR \\ \alpha = \delta_0(1 - 3.5(\theta_0 - TR)/\theta_0), & \theta_0 > TR \end{cases} \tag{3}$$

$$\text{Military:} \begin{cases} \alpha = \delta_0, & \theta_0 \leq TR \\ \alpha = \delta_0(1 - 3.8(\theta_0 - TR)/\theta_0), & \theta_0 > TR \end{cases} \tag{4}$$

Eqs. (3) and (4) take in the local temperature and pressure at a flight condition as well as the Mach number. The output is the thrust lapse, $\alpha \equiv T_i/T_0$. An additional parameter, TR, is defined as the throttle ratio. Mattingly suggests $TR = 1.08$ for modern low bypass ratio turbofans.

To calculate the thrust lapse, the temperature and pressure during a mission segment are determined using MATLAB's standard atmosphere model (atmoscoesa). The Mach number is set based on the mission segment, or calculated from the aircraft velocity and local speed of sound.

1.2 Constraints

Relevant constraint equations were determined based on requirements from the RFP. All of the equations input and output T/W and/or W/S. Constraints for catapult launch and recovery also depend on the initial takeoff weight.

1.2.1 Dash, Cruise, and Ceiling

From the RFP, the aircraft dash Mach number is required to be a minimum of 1.6 at 30,000 ft for the air to air mission at maximum thrust. For the strike mission, the dash speed is required to be Mach 0.85 at sea level at military thrust. Eq. (5) defines the constraint for the dash requirement.

$$\frac{T}{W} = \frac{qC_{D_0}}{W/S} + \frac{W}{S}\left(\frac{K}{q}\right) \tag{5}$$

where $q \equiv 0.5\gamma p M^2$ is the dynamic pressure, C_{D_0} is the parasitic drag coefficient, and $K \equiv 1/(\pi A R e)$. Eq. (5) is equivalent to a constraint for steady-level cruise, which is used for the cruise mission segments. For the ceiling constraint, a small gradient of 0.001 is added to Eq.(5). The RFP does not define a ceiling requirement, but it is included for completeness.

1.2.2 Turn Rate

For the air to air mission, a minimum sustained turn rate of 8 deg/s at 20,000 ft is required. A system of equations (6) for turn rate and velocity is created using equations from Raymer [4].

$$\begin{aligned} n &= \sqrt{\left(\frac{\dot{\psi}V}{g}\right)^2 + 1} \\ \frac{W}{S} &= \frac{q}{n}\sqrt{\frac{C_{D_0}}{K}} \\ \frac{T}{W} &= \frac{qC_{D_0}}{W/S} + \frac{W}{S}\left(\frac{n^2K}{q}\right) \end{aligned} \tag{6}$$

$\dot{\psi}$ is the turn rate in rad/s. Since q is a function of velocity, substituting the equation for n into the others yields two equations with W/S as the input and T/W and V as the output. Since velocity changes based on the input, the thrust lapse correction must be calculated for each W/S.

1.2.3 Vertical Load Factor

A minimum vertical load factor of 7g is required at mid mission weight. The equation for the required wing loading is

$$\frac{W}{S} = \frac{qC_{L_{\max}}}{n_z} \tag{7}$$

where n_z is the vertical load factor.

1.2.4 Climb Rate

The RFP lists point requirements for single engine rate of climb (SEROC) at takeoff and approach . They are 200 ft/min and 500 ft/min respectively. An equation for climb rate is used from Raymer, and is modified to output the required T/W

$$\frac{T}{W} = \frac{V_\gamma}{V} + \frac{\rho V^2 C_{D_0}}{2(W/S)} + \frac{2K}{\rho V^2}\frac{W}{S} \tag{8}$$

where V_γ is the climb rate. Additional factors from Martins are applied to Eq. (8) for one engine inoperative (OEI), maximum continuous thrust, and tropical day temperatures.

1.2.5 Takeoff

Given a maximum allowable ground roll, s_{tog}, thrust to weight in terms of wing loading can be solved for using Eq. (9):

$$s_{tog} = \frac{k_1(W/S)_{TO}}{\rho[C_{L_{maxTO}}(k_2(T/W)_{TO} - \mu_G) - 0.72C_{D_o}]} \tag{9}$$

where $k_1 = 0.0447$, μ_G is the rolling coefficient of friction, and k_2 is given by Eq. (10):

$$k_2 = 0.75(\frac{\lambda + 5}{\lambda + 4}) \tag{10}$$

where λ is the engine bypass ratio.

1.2.6 Landing

According to Roskam, the landing field length is given by Eq. (11):

$$s_{fl} = 0.3 * V_A \tag{11}$$

where s_{fl} is given in feet and V_A, the approach speed, is in knots. Approach speed is given by Eq. (12):

$$V_A = 1.2 * V_{SL} \tag{12}$$

where V_{SL} is given by Eq (13). V_{SL} must be converted to knots.

$$V_{SL} = \sqrt{\frac{2(W/S)}{\rho * C_{L_{max}}}} \tag{13}$$

1.2.7 Catapult Launch

The RFP sets the catapult minimum end speed using four requirements. They are repeated here.

1. An end speed which results in the CG position of the aircraft sinking no more than 10 feet from its position at the end of the power stroke, with a deck run not to exceed 32 feet (distance from the end of the power stroke to round-down), with cockpit control position held either fixed or free or controls active.
2. The speed represented by 90% of the maximum lift coefficient, power off, out of ground effect.
3. The minimum airspeed at which the aircraft has a longitudinal acceleration of 0.065 g (2.0913 ft/sec2) at zero flight path angle.
4. If multi-engine, the minimum aircraft control speed with one engine inoperative.

The first requirement is interpreted as limiting the distance the aircraft can drop after flying past the round-down. The aircraft reaches its end speed at the end of the power stroke before accelerating for the 32 ft deck run. The aircraft then flies off the carrier deck.

The second requirement end speed can be calculated as a function of W/S.

$$V_{\text{end},2} = \sqrt{\frac{2}{\rho \cdot 0.9 C_{L_{\max}}} \frac{W}{S}} \tag{14}$$

Assuming that the aircraft can quickly achieve $0.9C_{L_{\max}}$ as it leaves the deck, the aircraft will be in level flight since it's velocity will be at least $V_{\text{end},2}$. Thus, the first requirement is considered to be satisfied since the aircraft will not sink after leaving the deck. This implies that the end speed that satisfies the first requirement is less than $V_{\text{end},2}$.

For the third requirement, level flight is assumed, with longitudinal acceleration being a minimum of 0.065g.

$$\frac{T-D}{W} = 0.065 \quad \text{and} \quad L = W \tag{15}$$

Expanding the expressions in (15) and combining them together yields an expression for minimum airspeed as a function of W/S, T/W, and other aircraft parameters.

$$\frac{T}{W} - \frac{\rho V^2 \left(C_{D_0} + K \left(\frac{2}{\rho V^2} \frac{W}{S} \right)^2 \right)}{2(W/S)} = 0.065 \tag{16}$$

The minimum airspeed can be found by solving equation (16) for a specified W/S and T/W.

The minimum aircraft control speed for the fourth requirement is interpreted to be the minimum speed where a SEROC of 200 ft/s can be achieved at takeoff. Since the maximum takeoff weight allowed by the RFP is 90,000 lb, the minimum speed is set to 131 kts. This is found using the catapult performance curves provided in the RFP. If the SEROC requirement is satisfied, then the minimum speed for aircraft control will be less than or equal to the velocities specified from the second and third requirements for catapult end speed.

1.2.8 Recovery

The RFP defines the arrestment engaging speed to be 5% greater than the approach speed. The approach speed is required to 10% above stall speed, but shall be less than 145 kts. An additional point requirement lists the maxiumum wind-over-deck (WOD) to be 15 kts. A relationship between stall speed and arrestment speed can be defined as

$$V_{\text{stall}} = V_{\text{eng}}/1.05/1.1 + 15 \text{ kts} \tag{17}$$

Eq. (17) assumes that all speeds (engaging, approach, and stall) are defined as relative speeds. Thus, the true aircraft stall speed is 15 kts faster due to the minimum WOD. The equation can be substituted into the constraint equation for aircraft stall.

$$\frac{W}{S} = \frac{1}{2}\rho\left(\frac{V_{\text{eng}}}{1.05 \times 1.1} + 15 \text{ kts}\right)^2 C_{L_{\max}} \tag{18}$$

The maximum allowable engaging speed is found using the arresting gear performance curves provided in the RFP. The engaging speed is a function of the landing weight and increases as the weight decreases. At 40,000 lb, the engaging speed is capped to a maximum value of 145 kts. This satisfies the RFP's approach speed requirement.

2 Sizing Plot

Weight fractions for each constraint are defined by the mission segment they are most related to. They are listed in Table 1. For mission segments related to approach or landing, the maximum landing weight is used as defined by the RFP

Table 1: Constraints and corresponding mission segments for weight fractions, velocities or Mach numbers, and altitudes.

Constraint	Mission Segment
Dash	Dash acceleration before combat
Turn rate	Combat
Vertical load factor	Combat
Cruise	Cruise out (cruise 1) and cruise back (cruise 2)
Ceiling	Cruise out (cruise 1)
SEROC takeoff	Takeoff
SEROC approach	Maximum landing weight
Climb rate	Climb segments before cruise (both missions), and combat (strike)
Takeoff	Takeoff
Landing	Maximum landing weight
Catapult	Takeoff
Recovery	Maximum landing weight

2.1 Assumptions

Certain assumptions are made for certain constraints, since some aircraft design and performance parameters are unknown. The assumptions and their justifications are listed below.

- C_{D_0} and K are multiplied by two for the supersonic air to air dash. This is based on drag polars from Nicolai and accounts for the increase in drag at supersonic conditions.
- The velocity for the vertical load factor constraint was set at Mach 0.95. This was based on comments in Nicolai where most fighter aircraft have similar speeds for maximum vertical load factor.
- The ceiling constraint does not come from the RFP. A ceiling altitude of 50,000 ft is selected with the Mach number identical to the cruising Mach number. This may be unrealistic, since the cruise Mach number will change with altitude. Therefore, the ceiling constraint is currently only illustrative and will need to be revised.
- The climb rate requirement is more constraining when the climb velocity is reduced. For takeoff SEROC, the velocity is set as the catapult endspeed for a 90,000 lb load. For approach SEROC, the velocity is set as the maximum engaging speed for a 70,000 lb aircraft. For the climbs before cruise, a climb rate a 500 ft/min is defined from Nicolai, which cites MIL-C-5011C [5]. The combat climb for the strike mission is set at 12,950 ft/min which comes from the maximum combat climb rate for an interdiction mission performed by an F/A-18E/F [6].
- Takeoff from a runway is assumed to be half flaps. The rolling coefficient of friction is set to $\mu = 0.025$ based on MIL-C-5011C.
- Runways landings are assumed to be at full flaps.
- Catapult takeoff and arrested recovery are both assumed to be at full flaps. This reduces the aircraft's stall speed, improving both constraints.
- Roskam [7] states that military takeoff requirements are typically given by maximum allowable groundroll. For Navy fighter aircraft, Roskam gives a maximum allowable ground roll of 2500 feet. Minimum military runway length at airbases that the F-18 units operate from is 8,000 feet according to the FAA airport database [8], so 2500 feet is deemed to be an acceptable number for takeoff ground roll to meet military requirements.
- For land-based runway landings, the field length is assumed to be 6500 feet. Roskam [7] states that this requirement is usually given by the RFP, which it is not in this case, so the minimum runway length of 8,000 feet is used as a benchmark. Given this minimum runway length, 6500 feet for obstacle clearance and landing is deemed to be acceptable.

2.1.1 Drag Polars

The drag polar is generally given by Eq. (19):

$$C_D = C_{D_0} + KC_L \tag{19}$$

where K is given by Eq. (20):

$$K = \frac{1}{\pi e AR} \tag{20}$$

An initial estimate for parasitic drag is found using Eq (21), which is given in Roskam [7].

$$C_{D_0} = c_f \frac{S_{wet}}{S_{ref}} = c_f \frac{10^{c+dlog10(W_{T0})}}{W_{T0}/(W_{T0}/S)} \tag{21}$$

where c_f is the skin friction coefficient and c and d are regression constants. Given by Roskam for a Navy fighter, $c_f = 0.004$, $c = -0.1289$, and $d = 0.7506$. An initial weight estimate of 80,000 lbs from the initial weight sizing is used for W_{TO}. Wing-loading from a similar aircraft, the F-15 [9], is used for the initial estimate. This wing loading is 112 lb/ft^2, which is nearly identical to the average wing loading of the fighter jets investigated in Assignment 1.

This leads to an initial estimate of $C_{D_0} = 0.0199$ (clean). The change in C_{D_0} for different configurations are found using Roskam. Raymer [4] is used to estimate the change in C_{D_0} for each tank and pylon. These values are given in Table 2. For sizing plot estimations, the lowest efficiency and highest ΔC_{D_0} is used for a conservative estimate on drag.

Table 2: ΔC_{D_0} for varying aircraft configurations.

Configuration	ΔC_{D_0}	Efficiency (e)
Clean	0	0.8-0.85
Half flaps	0.01-0.02	0.75-0.8
Full flaps	0.055-0.075	0.7-0.75
Landing gear	0.015-0.025	no effect
Tank (each)	0.0007	no effect
Pylons (each)	0.0001	no effect

2.2 Design Point and Results

The initial design point is selected for a air to air combat range of 800 nm and a combat time of 2.9 min. The dash Mach number is set to 1.6. The corresponding strike range is 945 nm with a dash Mach number of 0.9. The engine used for the analysis is the F110-GE-132. The final design point has a maximum takeoff thrust-to-weight ratio of 0.83 and a wing loading of 83.5 lb/ft^2. The military thrust T/W is 0.44. The sizing plot for the air to air mission is shown in Figure 1 and for the strike mission in Figure 2. For the air to air

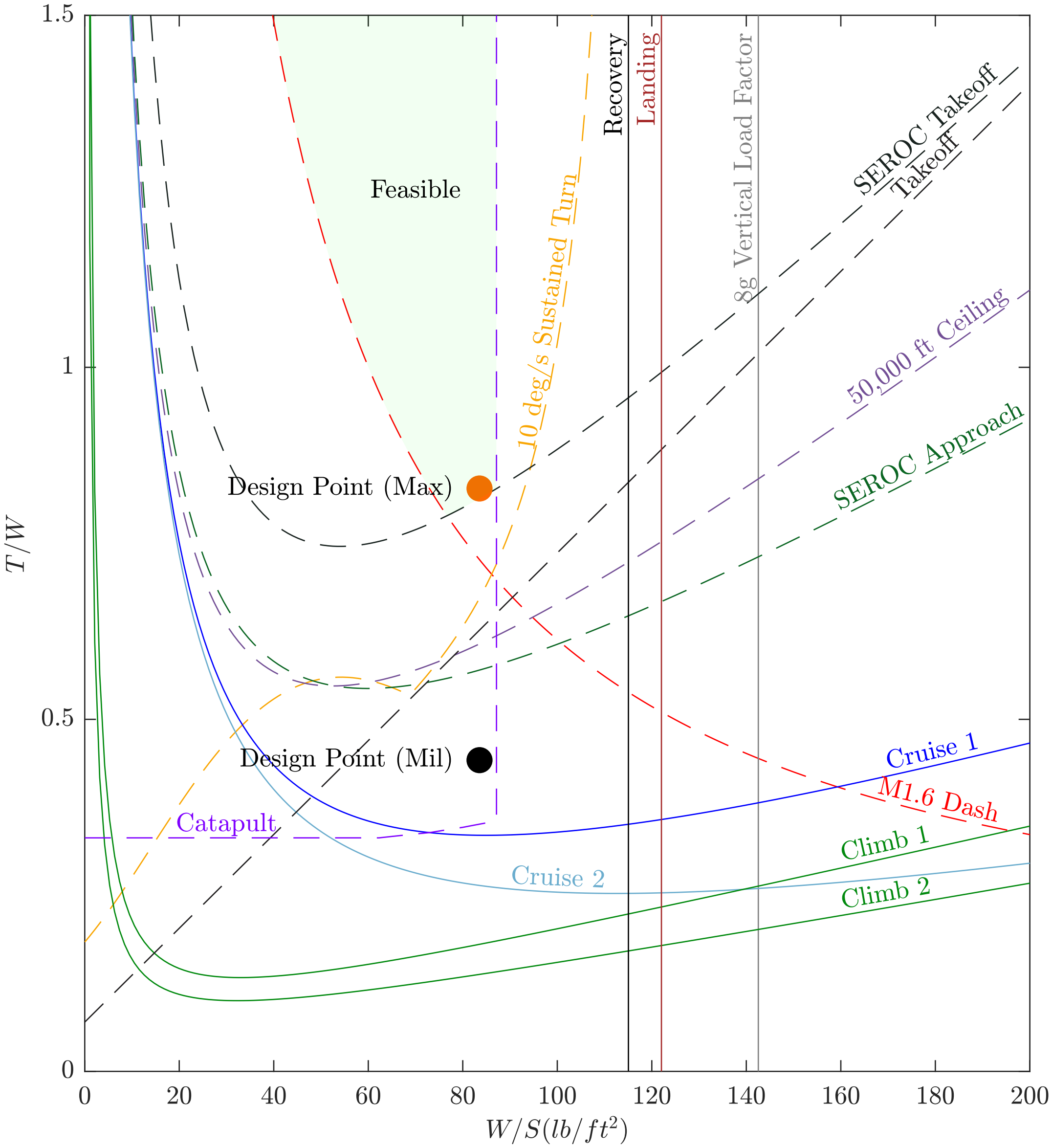

Figure 1: T/W-W/S sizing plot for the air to air mission. Dashed lines represent maximum thrust constraints. Solid lines are military thrust.

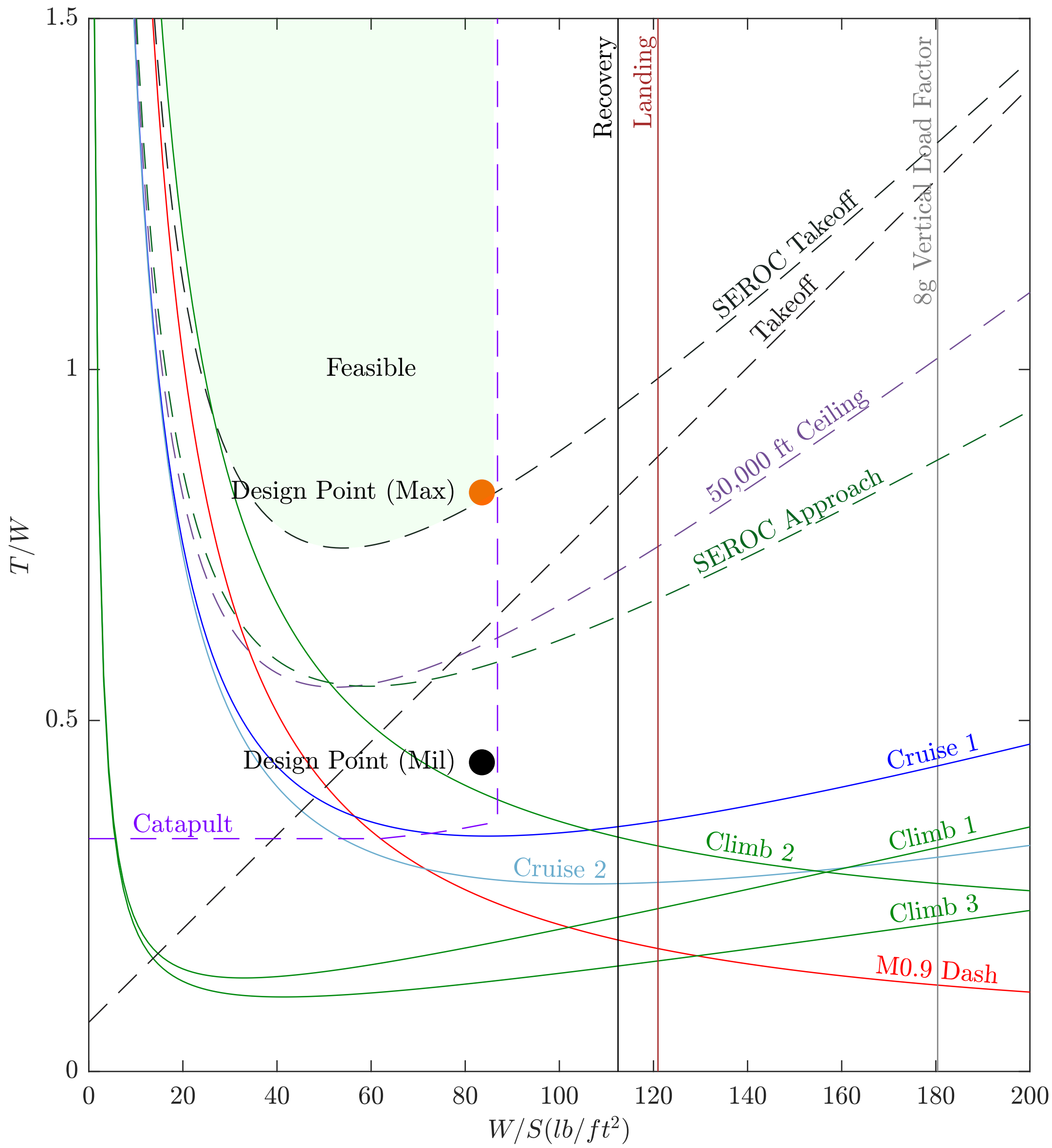

Figure 2: T/W-W/S sizing plot for the strike mission. Dashed lines represent maximum thrust constraints. Solid lines are military thrust.

3 Group Work Split

Table 3: Work Split

Person	Work Percentage	Brief Description of Work Done
Michael Chen	30%	Derived constraint equations, wrote code for sizing plot analysis, helped write report.
Charles Choi	15%	Setup CAD PLM within Teamcenter 14, helped gather equations.
Cristina Erskine	15%	Researched constraint equations and factors, helped review sizing plot analysis code, helped write report.
James Gold	15%	found thrust correction factors, helped collect data for sizing plot, researched constraint equations.
Santiago Ramos-Assam	15%	Gathered data, helped write thrust code, and helped write report.
Thomas Sheridan	10%	Helped derive sizing plot equations. Revised cost code.

References

[1] Joaquim R.R.A. Martins. *The Metabook of Aircraft Design*. Dr. Martins, Joaquim R.R.A., 2021.

[2] Jack D. Mattingly, William H. Heiser, and David T. Pratt. *Aircraft Engine Design*. American Institute of Aeronautics and Astronautics, Inc., 2002. ISBN: 978-1-60086-144-4.

[3] Leland M. Nicolai. *Fundamentals of Aircraft Design*. American Institute of Aeronautics and Astronautics, 2010. ISBN: 978-1-60086-751-4.

[4] Daniel P. Raymer. *Aircraft Design: A Conceptual Approach*. American Institute of Aeronautics and Astronautics, 2018. ISBN: 9781624104909.

[5] MIL-C-5011C Military Specifications. *Standard Aircraft Characteristics and Performance, Piloted Aircraft*. 1951.

[6] *Standard Aircraft Characteristics F/A-18E Super Hornet*. NAVAIR00-110AF18-6. Boeing. 2001.

[7] Jan Dr. Roskam. *Part 1: Preliminary Sizing of Airplanes*. Roskam Aviation and Engineering Corporation, 1985.

[8] *Airport Data*. 2023. URL: `https://www.faa.gov/air_traffic/flight_info/aeronav/aero_data/Airport_Data/`.

[9] *F-15A Flight Manual*. 1984. URL: `https://www.scribd.com/document/621397157/F-15A-Flight-Manual` (visited on 09/10/2025).