TASS: A Toolkit for Aircraft Sizing and Synthesis

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Abstract

A Toolkit for Aircraft Sizing and Synthesis (TASS), capable of performing sizing and synthesis calculations in the context of conceptual design of aircraft is developed in Matlab.[3] TASS implements energy-based constraint and weight fraction approach for the mission sizing analyses and provide the user with a design point that is a function of *thrust-weight ratio* and *wing-loading*. The performance of TASS is benchmarked against the known metrics of a transonic jet fighter aircraft F-86L Sabre (Sabrejet).

1 Introduction and Motivation

Design of aircraft is subject to tens of thousands of constraints that span across a variety of disciplines such as aerodynamics, structures, controls and performance.[1,2,7,8] Examples of such constraints, to name a few are: achieving a long cruise range, minimizing the take-off distance, fuel-efficient engines, stealth capabilities for reconnaissance and so on. These constraints are indeed the ones that drive the design and play a pivotal role in shaping the end-design. There has been an increased interest in exploring more at initial stages of design to identify conventional as well as non-conventional configurations – a strategy that helps one to get a better insight of potential configurations that can meet the design requirements and eliminate restrospective changes that may be due at later stages in design process, that are known to be prohibitively expensive.

Similar motivations have led to the development of tools that ably perform conceptual analysis in various platforms.[6,9] To this end, this work too aims to develop a toolkit in Matlab[3] known shortly as TASS, that performs some of the very early phases of aircraft design *i.e.,* the sizing and synthesis. The scope of the current work is limited to the conceptual design phase of aircraft design; more advanced phases in aircraft design (preliminary, detailed design *etc.*) fall beyond the scope of the current work. Nevertheless, modularity is a key consideration in the development of the toolkit, which enables further advancements a function of time.

Energy based constraint analyses form an attractive way to start with aircraft design. The main advantage of energy-based approach over conventional approaches is that it employs Lagrangian paradigm of mechanics, as opposed to Newton's world of vector mechanics. The key idea is that aircraft is treated as a system that converts energy from one form to another as the mission progresses. For example, combustion in the engines convert the chemical energy of the fuel into thermal energy, which in-turn accelerates the gases to rotate the turbines to provide mechanical energy to sustain motion. It is easier to think in terms of scalars such as kinetic energy (depends on velocity) and potential energy (depends on position), compared to resolving forces (e.g. lift, thrust) in along different directions (e.g. vertical, horizontal). Due to these advantages, TASS preferably employs energy based constraint analyses. The mathematical and physical models used in individual disciplines are explained as and when they are introduced in later sections and are not explained here in the spirit of brevity.

This report is organized as follows. Section 4 outlines the mathematical models behind the aircraft sizing and synthesis procedure. Section 2 outlines the functionality that is expected from the toolkit. Section ?? contains detailed step-by-step instructions on the working of the tool with the help of an example. Section 6 concludes the report highlighting the key aspects of the tool and lays-out scope for further improvements to the toolkit.

2 Requirements of the Toolkit

A brief introduction of the concept under study and a summary of the mission and requirements are outlined next. The conceptual design process begins with a defined set of requirements. These requirements lay-out specific constraints and design goals that the end-system must be capable of achieving. These goals and constraints are often presented the form of Request for Proposal (RFP). RFP for the fighter is given in Appendix ??.

Functional requirements and performance requirements

3 Getting Started

This section is devoted to provide a high-level overview of the working of the software. All the discussions in this section are organized in terms of the benchmarking test case Sabrejet F-86 L.

3.1 Installation

TASS uses native Matlab code for all of its functionality – including initialization, iterative calculations and graphics, therefore a working version of Matlab[3] is sufficient. The software is tested to work on both UNIX and Windows based workstations. The source code can be obtained by using `git clone https://github.com/komahanb/tass.git` from a *terminal* or *shell* program or by downloading `tass-master.zip` file and extracting it in a working folder of convenience.

3.2 Input Layout

A Graphical User Interface (GUI) is designed to collect all the mission-specific inputs that the user supplies to the software. From an user-standpoint these input parameters are decided based on the complete break-down of mission requirements (e.g. humanitarian, rescue, military missions). Table ?? presents the typical inputs that the user is expected to provide to the software.

3.3 Output Layout

Output layout contains a collection of information interms of values and plots that the user would expect to see from the software. The following are the list of values, tables and plots that TASS is able to present to the user.

4 Architecture of the Toolkit

This section provides an outline of the theory, physical and mathematical models used in TASS. A rather comprehensive discussion on these topics can be found in the literature.[1,2,4,7,8] Figure 4.1

provides a generic overview of the elements involved in the sizing and synthesis process. As it can be seen, *constraint analyses* and *weight estimations* are pivotal in producing the design.

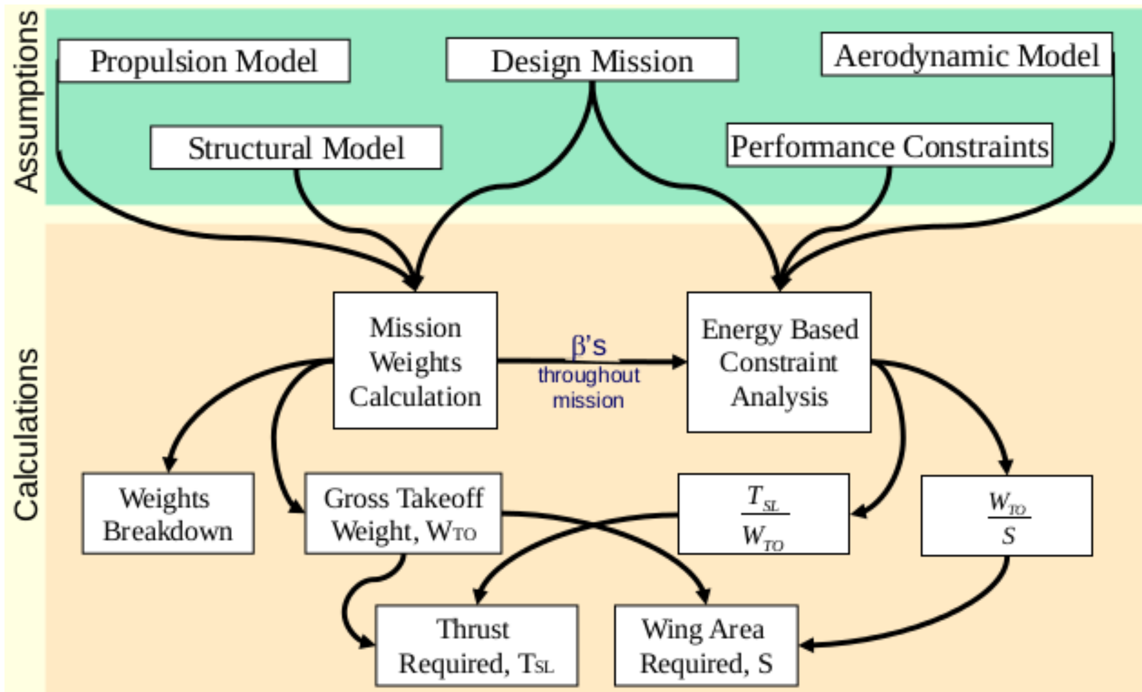

Figure 4.1: A top level overview of sizing and synthesis process implemented in TASS.[5]

4.1 Standard Atmosphere Model

TASS has offers the flexibility to choose between two popular standard atmosphere models to the users:

(a) U.S. Standard Atmosphere model[10]

(b) Committee on Extension to the Standard Atmosphere (COESA) model[10]

These models are used to obtain the temperature, speed of sound (Mach number), pressure and density as a function of height in the calculations. The default model used in the tool is the U.S. Standard Atmosphere model.

4.2 Mattingly Energy Equation

The performance constraints and requirements are set as functions of *thrust loading* (thrust-to-weight ratio) and *wing loading*, the two sizing parameters that contain key information about the top level characteristics of the system.[4] The Mattingly Master Enerygy equation is:

$$\frac{T_{SL}}{W_{TO}} = \frac{\beta}{\alpha}\left\{\frac{qS}{\beta W_{TO}}\left[K_1\left(\frac{n\beta W_{TO}}{qS}\right)^2 + K_2\left(\frac{n\beta W_{TO}}{qS}\right) + C_{D_0} + \frac{R}{qS}\right] + \frac{1}{V}\frac{d}{dt}\left(h + \frac{V^2}{2g_0}\right)\right\} \tag{4.1}$$

Table 1 contains a short definition of the parameters in Eq. 4.1.

Table 1: Parameters in Mattingly Energy Equation

Parameter	Description	English Unit	SI Unit
T_{SL}	sea-level thrust	lb	N
W_{TO}	take-off gross weight	lb	N
q	dynamic pressure	lb/ft^2	N/m^2
S	wing planform area	ft^2	m^2
C_{D_0}	drag at zero lift	no unit	no unit
K_1			
K_2			
q	load factor	no unit	no unit
R			
V	velocity(speed)	ft/s	m/s
h	altitude from sea level	ft	m
g_0	gravity at sea level	ft/s^2	m/s^2
α			
β	instantaneous weight fraction		

4.3 Constraint Analysis

By manipulating Eq. 4.1 various constraints pertaining to the mission can be derived. Detailed derivation and treatment of such constraints can be found in Mattingly *et al.*[4]

4.3.1 Constant Altitude/Speed Cruise

4.3.2 Constant Speed Climb

4.3.3 Constant Altitude/Speed Turn

4.3.4 Horizontal Acceleration

4.3.5 Takeoff Ground Roll (lots of Thrust)

4.3.6 Takeoff Ground Roll (not so much Thrust)

4.3.7 Braking Roll

4.3.8 Service Ceiling

4.4 Weight Estimation

The takeoff gross weight W_{TO} is estimated as

$$W_{TO} = W_C + W_P + W_E + W_F \tag{4.2}$$

where W_C is the crew weight, W_P is the payload weight, W_E is the empty weight and W_F is the fuel weight.

5 Conceptual Design of the Benchmark Fighter

The comparison of the design obtained using the tool with known configuration of the aircraft follows next. Table **??** presents the performance parameters that are calculated using the tool with that of the existing data. A good agreement between values demostracte the accuracy of the tool.

5.1 Perturbations of Constraints

A good end-result of the conceptual design phase is to identify answers to the following questions?

1. Will it work?
2. What does it look like?
3. What requirements drive the design?
4. What tradeoffs should be considered?
5. What should it weigh and cost?

6 Summary

This work presented a generic toolkit that performs sizing and synthesis of the aircraft configurations at the conceptual design level. The toolkit is provided with a graphical user-interface that helps non-expert users to simulate different requirements at the same time. It is validated against a known configuration of F-86 Sabrejet.

References

[1] J. P. Fielding. *Introduction to Aircraft Design*. Cambridge University Press, New York, NY, 1st edition, 1999.

[2] D. Howe. *Aircraft conceptual design synthesis*. Professional Engineering Publishing, London, 1st edition, 2000.

[3] MATLAB and Statistics Toolbox Release 2015a. *version 8.5.0 (R2015a)*. The MathWorks Inc., Natick, Massachusetts, 2015.

[4] J. D. Mattingly, W. H. Heiser, and D. T. Pratt. *Aircraft Engine Design*. American Institute of Aeronautics and Astronautics, Reston, VA, 2nd edition, 2002.

[5] D. Mavris. *Fixed Wing Aircraft Design I*. Lecture Notes, Georgia Institute of Technology, 2015.

[6] N. E. Antoine and I. M. Kroo. Framework for Aircraft Conceptual Design and Environmental Performance Studies. *AIAA Journal*, 43, No. 10, 2005.

[7] L. M. Nicolai. *Fundamentals of Aircraft Design*. E. P. Domicone Printing Services, Fairborn, OH, 1st edition, 1975.

[8] D. P. Raymer. *Aircraft Design: A Conceptual Approach.* American Institute of Aeronautics and Astronautics, Reston, VA, 3rd edition, 1999.

[9] D. P. Raymer. Modern Use of Spreadsheet Methods for Aircraft Design, Sizing, and Performance Analysis. AIAA Paper, 2004-0534, 2004.

[10] 1976 U.S. standard atmosphere. *United States Committee on Extension to the Standard Atmosphere.* U.S. Government Printing Office, Washington, D.C., 1976.

A RFP for Benchmarking Test Case

B Flexibility of the Tool

B.1 Versatility of the Tool

1. The Graphical User Interface (GUI) takes the set of inputs and perform the analyses. As long as the inputs specified are within the validity of the underlying mathematical models, the tool will work for any set of requirements as explained in Section **??**.

2. TASS can operate with both English and SI units

3. TASS employs interpolations and extrapolations whenever it encounters data that are be rather difficult to supply or unavailable (e.g.)

B.2 Challenges and Cons

1. Since it is extremely laborious to implement sanity checks on the user-supplied values, it is recommended that the users proactively consider the physical meaning of the values supplied (e.g. range, rate of climb)