Mass Estimating Relationships for Liquid Rocket Engines

Extended Abstract

I. Background

Total mass estimation of launch vehicles and space systems during the early design process is typically done by combining the mass estimations of the various components of the system. Mass estimation of various components is also a key part of rapid trade-off analysis and design optimization in early conceptual design. The accuracy of component mass estimates can have a large effect on the overall time and cost of development of these systems. Mass estimates of rocket engines, tanks, structure, etc. generally come from developing relationships based on mass data of past systems and previously developed individual components. The way these mass estimating relationships (MERs) are developed can vary between institutions or even within an institution. The data sets used for developing MERs can also vary widely depending on the data the institution has access to. Often published MERs do not include the data set used, so it is unclear where differences in estimations come from. For liquid rocket engines, many MERs are simple linear regressions based solely on thrust, often with some percentage added to account for related structural mass. For example, the textbook *Space Propulsion Analysis and Design* by Humble et al. [1] lists separate thrust-based MERs for launch vehicle engines, in-space engines, and monopropellant thrusters. These relations are often used as the base for other MERs that add various related structural mass estimates. One issue with these MERs, particularly for the launch vehicle engines, were created from a small data set and do not reflect the mass variation between cryogenic and storable propellants. Other engine MERs have been developed to include additional parameters such as chamber pressure and propellant type within the relation, but have limited information about the data or methods to create the MER. Simple thrust relations can be optimal for use early in the design process when only generalized estimates are needed and many parameters are still unknown. However, when using higher fidelity modeling and simulation tools, more parameters are specified early on which could be included in the engine MERs and possibly increase accuracy of the mass estimates.

II. Motivation

Some recent work at the Aerospace Systems Design Lab (ASDL) at Georgia Tech has focused on the conceptual design of lunar landers [2]. The Dynamic Rocket Equation Tool (DYREQT) is an internally developed space systems conceptual design tool built on NASA's MDAO framework and is the primary analysis and optimization tool being used for the current lander studies [3]. Because engine mass is a significant percentage of the overall mass in a lunar lander, accurate engine mass estimates are highly important for this application. The current MERs used in DYREQT's engine module are a variation of the MERs from Humble et al. [1], and shown below in equations 1, 2, and 3.

Monopropellants:

$$m_E = \frac{F}{g_0(-3.7405*10^{-10}*T^4+7.1685*10^{-7}*T^3+(-5.2221*10^{-4}*T^2)+0.18761*T-0.039763} \quad (1)$$

Bipropellants:

$$\textit{For thrust<50000: } m_E = \frac{T}{g_0(0.0006098*T+13.44} \quad (2)$$

$$\textit{For thrust>50000: } m_E = \frac{T}{g_0(25.2*\log(T)-80.7} \quad (3)$$

+1% of engine mass for propulsion management (valves, regulators, filters, etc.)
+15% of (engine mass + prop management) for miscellaneous hardware (plumbing, brackets, insulation etc.)

As mentioned before, these MERs do not account for differences in propellant type, but are based solely on thrust. Figure 1 shows the MERs compared to a small sample of actual engine data. It can be seen that the MER is fairly accurate for large LOX/Hydrogen engines, but greatly overestimates the masses of LOX/Hydrocarbon and other storable propellant engines.

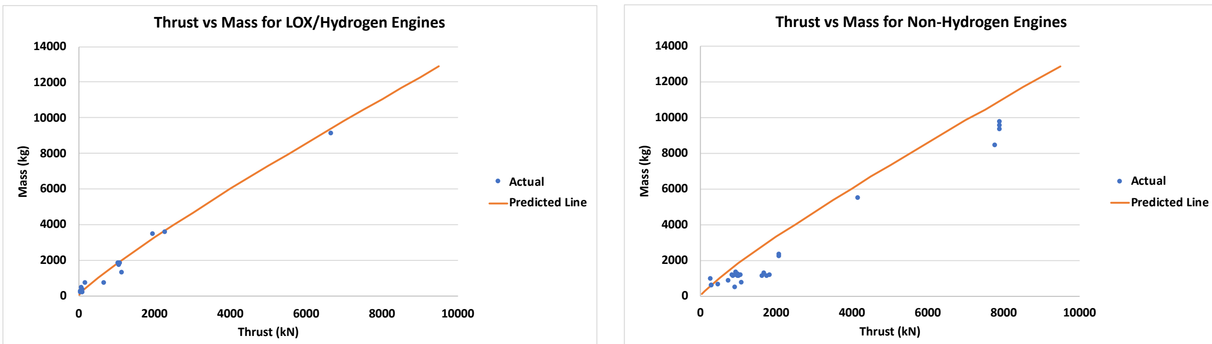

Fig. 1 Current MER compared to actual data for LOX/hydrogen and non-hydrogen engines

The primary goal of this study is to update the currently used engine MERs by using a large database of both current and past engines, and to improve the accuracy of estimations by including additional variables such as propellant type(s) and propellant feed system. A secondary goal of this study is to develop length and diameter estimating relationships for liquid engines to be used in geometrical layout decisions. These dimensional envelope estimations will also be incorporated in DYREQT's geometry reasoning capability.

III. Lit Review

As previously mentioned, the MERs from Humble et al. [1] or variations of them are often used for general estimates by students or in early versions of design tools such as in DYREQT. Another variation of them is seen in Ref [4].

A 2002 research paper done at Georgia Tech's Space Systems Design Lab (SSDL) made an explicit comparison of several MERs developed by various researchers at NASA and in industry [5]. The propulsion system MERs have varying levels of specificity but most contain a single equation for the engine mass. They are derived from various aircraft and rocket systems.

A study by Zandbergen in 2015 developed MERs based on simple and multivariate regression techniques [6]. The results included simple thrust relations as well as relations that incorporated chamber pressure and engine cycle. The study was done on 47 engines divided into cryogenic propellants vs. semi-cryogenic and storable propellants, but generally looked at larger engines.

Other studies have looked at generating mass estimates based on the sum of all the separate engine parts, where some of the engine part masses are statistically based and some are physics based [7,8]. At this time models like this might require to many unknown engine parameters to be used in vehicle conceptual design.

IV. Methodology

This study relies heavily on having a large and accurate data set on a wide variety of liquid engines to both create and test the mass and envelope estimating relationships.
Data was collected on over 100 liquid rocket engines over a thrust range of .09N – 8000kN. The data included several different categories of liquid engines designed for various applications. Key parameters include vacuum thrust, type of propellant(s), feed-system, engine cycle, vacuum specific impulse, chamber pressure, and expansion ratio. Several weeks were spent collecting and verifying the data before narrowing down to the final database. The data was then cleaned and imported into statistical software for evaluation.

Various subsets of this data were explored and known physics-based relations were used to discover any useful correlations in the key parameters before creating the MERs. Subsets were created based on propellant type (hydrogen, hydrocarbon, non-hydrogen, monopropellants, hydrazine), propellant feed system (pressure-fed, pump-fed), engine category (launch vehicle, in-space, thruster), and engine cycle (open cycle, closed cycle). MERs were created for the entire engine set as well as each subset.

Mass estimating relationships were developed using both simple and multivariate regression techniques as well as various machine learning algorithms. Both linear and polynomial regressions were used. Machine learning algorithms included decision trees, bootstrap forest, boosted forest, neural networks, and others. K-fold crossover validation was used to validate each of the models. The resulting MERs were compared using a reserved test data set to establish the best performing MERs and envelope estimating relationships.

V. Preliminary Results/Conclusions

Preliminary results confirm that thrust is the primary predictor in mass estimation, at least for the larger engines. Other predictors do show up in some of the machine learning algorithms for improved results. Predictors for length and diameter have been more varied based on the method used. Separation into subsets based on propellant type gives improved estimates over the currently used DYREQT MERs. As more engine data becomes available, mass estimating relationships will continue to become more accurate and improve modeling capabilities of conceptual design tools.

References

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