Hybrid-Electric Propulsion Sizing and Experimentation for US Army UAS

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ABSTRACT

Military aircraft in future joint multi-domain operations will not have access to the same electrical infrastructure available to commercial aircraft and therefore, all but the smallest aircraft will continue to rely on liquid fuels. Due to the large number of different aircraft architectures that exist, a tool can size and optimize the propulsion system with integrated hybridization is important. In this study, current research efforts in developing a modular hybrid-electric propulsion optimization tool that can identify and size hybrid components and select their optimum configuration based on each aircraft's architecture and mission profile are discussed. Detailed compression ignition models are used in combination with an empirical electrical component model to determine the effects of hybridization on the power density, weight, and endurance of a single-propeller, fixed-wing aircraft, equipped with a parallel hybrid propulsion system. Experimental facilities that will be used for model validation are being developed at the Army Research Laboratory. Preliminary results indicate the difficulty of hybridizing large vehicles, due to the inherent weight problems associated with batteries, with local optima incorporating electric motor propulsion only achieved at greatly reduced mission requirements. Further research on different hybrid configurations, improved component models, and more detailed consideration of losses and additional required systems, such as thermal management, needs to be conducted in order to more accurately model hybrid-electric propulsion systems.

1.0 INTRODUCTION

Trade studies have been conducted for various hybrid electric configurations for large aircraft (Jansen 2017) and personal vertical take-off and landing aircraft (Snyder 2017), with many of these studies incorporating advanced configurations offering unique aerodynamic considerations (Hung 2012). The authors are unaware, of sizing codes with accurate performance maps for small (~20-200 kW) engines, electric machines and power electronics incorporated into a hybrid-electric vehicle. Additionally, the sizing codes must be capable of exploring the propulsion design space for a given requirement with sufficient fidelity to highlight research challenges specific to aviation systems. In this work an optimization framework with increasingly accurate component performance descriptions is developed, utilizing existing information available in the literature (Meyer 2017, Donateo 2019 and Schömann 2014). Model predictions for a small aviation-relevant intermittent combustion engine are calculated and validated with measured performance at ARL's Small Engine Altitude Research facility (SmEARF), and explored in an optimization routine that compares the results using to a simplified model representation of engine weight and specific fuel consumption. Future work will similarly address the differences between model representations and real performance data of other components such as power electronics, electric machines and batteries.

Sizing and optimization studies will initially rely on model descriptions and functional approximations of component performance and scaling laws (Deng 2018). Laboratory experimental component responses will be used to elucidate non-ideal behaviours, refine model descriptions, and to highlight interactional dynamics in these more complex electromechanical drivetrains. An initial module of this future experimentation capability focuses on the performance of aviation relevant electric machines with a simulated DC power bus. The performance of commercial-off-the-self (COTS) machines will be compared against manufacturer data and simplified functional descriptions with laboratory experimental studies probing the transient and dynamic performance attributes including thermal performance.

2.0 EXPERIMENTAL CAPABILITIES AND METHODOLOGY

ARL owns key experimental capabilities capable of characterizing hybrid electric components at altitude conditions. The primary facility, SmEARF, has capabilities of replicating ambient conditions up to 30,000 feet (9,144 m) following the international standard atmosphere (ISA) model, when determining the temperature and pressure for any given altitude. This facility enables experimentation of fully instrumented engine systems at different loading conditions and altitudes to obtain performance characteristics. It can additionally be used to observe performance of power electronics at simulated flight conditions. Another facility designed to characterize hybrid electric components is the Hybrid-Electric Optimization and Integration Laboratory (HEOIL). HEOIL will be used to understand the power combination effects between an engine component and electric motors when its design and build process is completed. HEOIL will be a state of the art facility allowing for the power combination of an engine and motor inputs configured in a variety of orientations(parallel, series, etc.) as well as the provide the ability to easily change any of its components through a modular design. HEOIL will also provide validation data sets for the hybrid-electric optimization and integration tool.

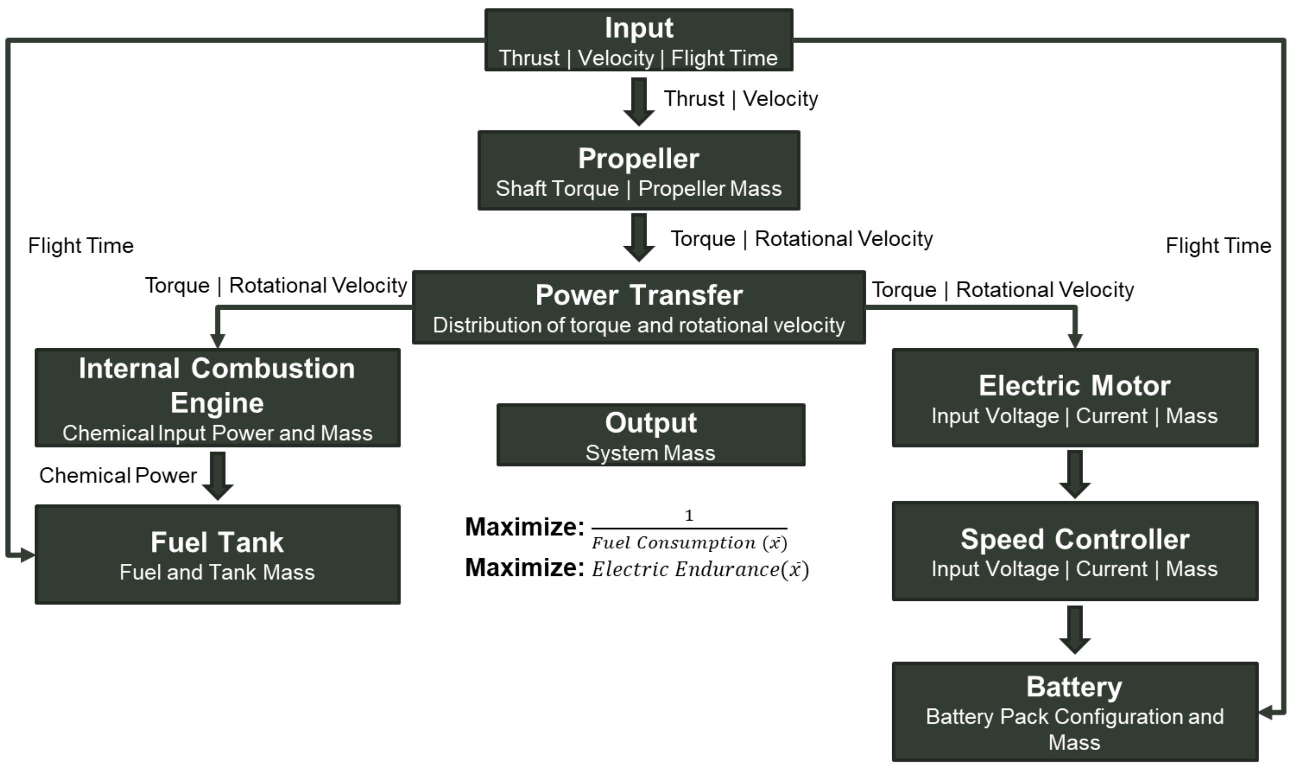

Figure 2-1: Base model algorithm for determining and optimizing power split between internal combustion engine and electric motor.

The algorithm for the hybrid-electric optimization code, which is the focus of this manuscript, is shown in Figure 2-1. The overarching goal is to develop a sizing tool, which will allow for the optimization of all components that are part of a hybrid system, based on key parameters, such as weight, endurance time, energy efficiency, silent capabilities and more. The tool will allow for the optimization of all components in the hybrid system based on key parameters, such as weight, endurance time, energy efficiency, silent capabilities, ect. The current capabilities of the tool optimize the distribution of power supplied between the engine and electric motor based on required power from the propeller. An optimum power density is determined for that particular mission profile once the weight of each component is calculated. The engine model was built using Ricardo Wave software, matching a maximum peak power of 160 kW. In order to obtain high fidelity results, brake specific fuel consumption maps were obtained from the high fidelity engine simulation for different power and engine speeds (RPM) spanning a range of altitude conditions. This information is used as the engine block in the Matlab/Simulink optimization script requiring power and altitude as inputs. The optimization tool then determines an engine RPM that returns the lowest fuel consumption. Motor and battery performance characteristics were based on empirical formulations.

3.0 RESULTS AND DISCUSSION

The 160kW engine results from the high fidelity Ricardo Wave software are shown in Figure 3-1, for a variety of different altitudes. The brake specific fuel consumption was calculated for each set of conditions, generating contours at discrete altitudes.

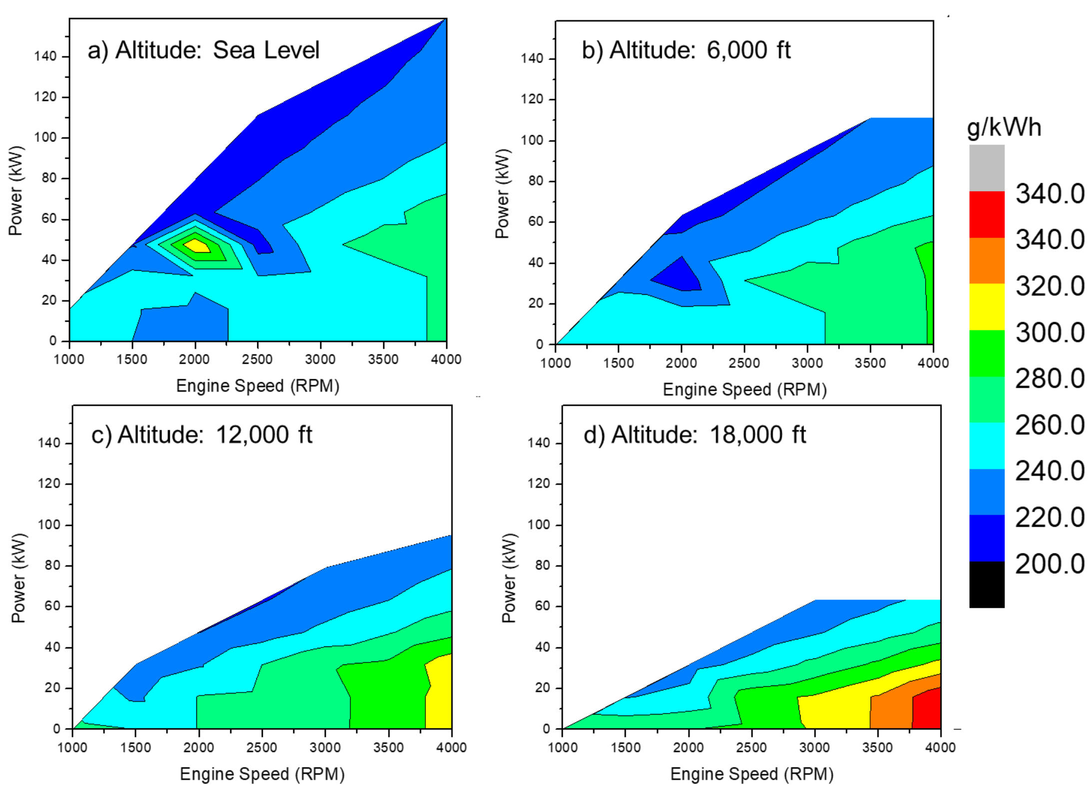

Figure 3-1: Brake Specific fuel consumption generated through Ricardo WAVE based on a 160 kW engine model for altitude conditions of a) Sea Level, b) 6,000 ft, c) 12,000 ft and d) 18,000 ft.

The maximum power curve as a function of engine RPM and altitude is shown in Figure 3-2. The engine's power limit observes the correct trend lines in terms of increasing with RPM and decreasing with increasing altitude, due to the reduction in ambient air density. This allows for the generation of an engine fuel consumption map, based on the power output of the engine, speed and altitude, which will be used by the Matlab/Simulink code, to optimize the power distribution between the engine and electric motor.

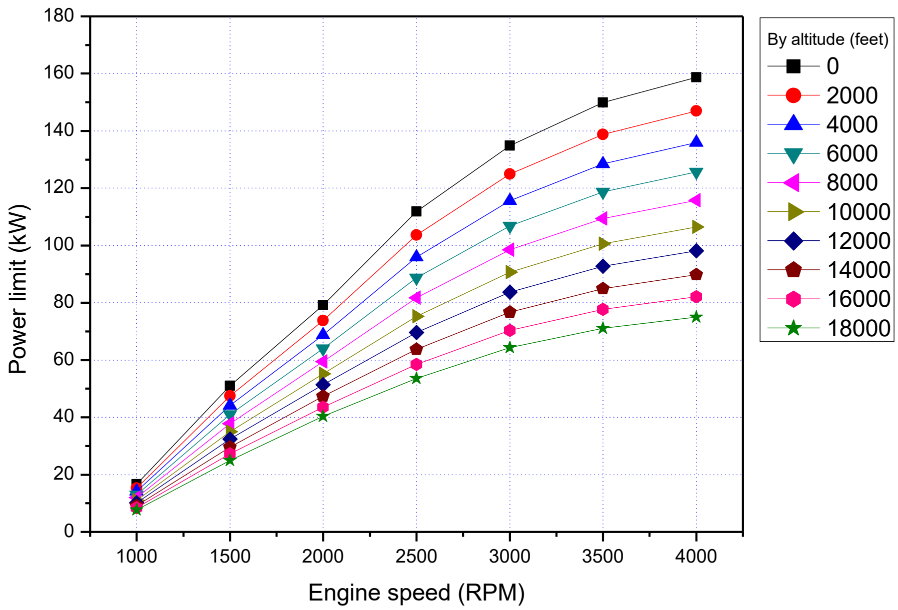

Figure 3-2: Maximum power curve as a function of engine RPM and altitude.

The primary inputs considered for this hybrid-electric propulsion simulation tool are the hybridization factor (HF), the flight profile, and the propeller rotational speed. The HF is determined as the ratio of the maximum electric motor power to the maximum engine power. A negative HF would imply that the engine is being used to charge the batteries, enabling extended use of the electric motor. The flight profile is determined by the altitude at a given time, in combination with the power required. Lastly, the rotational speed of the propeller is required as an input, in order to determine the respective electric motor and engine rotational speeds.

The simulation inputs used for the results presented in the current manuscript, are shown in Figure 3-3. Certain simplifications were used in order to obtain preliminary results. The HF as a function of time, is constant as it depends on the ratio of the size of the motor and engine, is shown in Figure 3-3a. For this case only constant recharging was considered for a given time period. As such the recharging period and rate was considered as an input to determine whether it would improve the overall results. Figure 3-3b is a simplified mission profile with a constant speed, climb, cruise and decent. The power output was fixed for each phase of the mission profile for simplicity, as shown in Figure 3-3c, with the goal of determining the optimum engine and motor size. In the current simulation, the aircraft weight reduction due to fuel consumption as it follows the mission profile was not considered. In addition, different fixed power outputs were used, defined by the mission factor, in order to observe the effects of reduced mission requirements. The propeller rotational speed profile is shown in Figure 3-3d. A 1:1 combining gearbox with a 1:1 reducing gearbox were used, in order to combine and convert the mechanical power from the engine and electric motor to the propeller. An overall constant transmission efficiency was considered that was independent of the flight conditions.

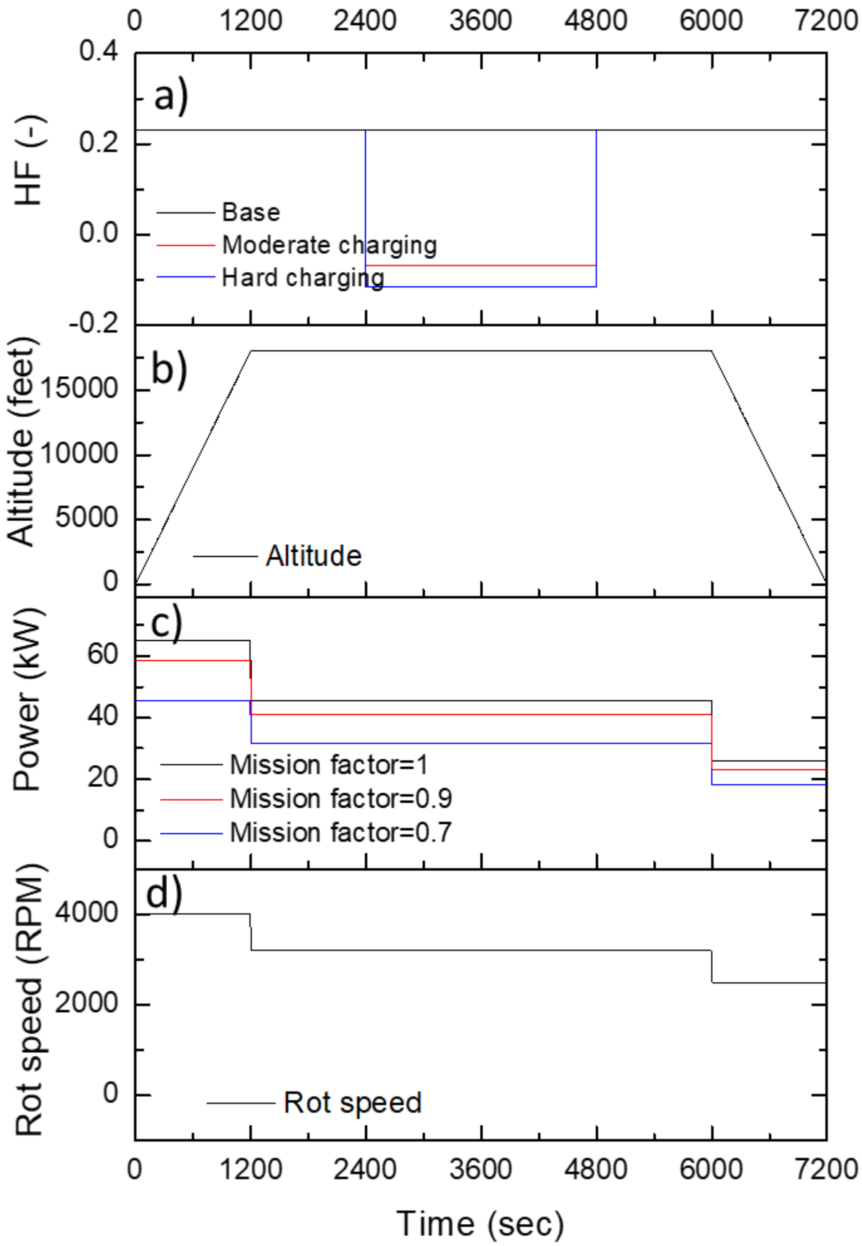

Figure 3-3: Example input parameters for hybrid powertrain based on a 120 minute flight profile. Graph (a) shows the hybridization factor, (b) the flight profile, (c) Mission factor, and (d) engine rotational speed.

Results of the current simulation without battery recharging can be observed in Figure 3-4, for four mission factors, 0.9, 0.7, 0.5 and 0.3. The first observation is that as the mission factor decreases the power-to-mass ratio increases. This stays consistent as the maximum motor power is increased, and can be attributed to the fact that as the mission power gets reduced, the weight of the required batteries is also significantly reduced. It was also observed, that the power-to-mass ratio monotonically decreases with increased hybridization factor (electric motor maximum power). The slope of the power-to-mass ratio versus hybridization factor decreased with decreasing mission factor. This hinted that for high load missions, hybridization only served to reduce the overall power-to-mass ratio, where the weight savings of a smaller engine and carrying less fuel was far outweighed by the additional battery weight. An optimized solution was only achieved at very low mission factors (<0.3), requiring very high hybridization factors (>60%). In this case however, the higher hybridization factor proved to have a better power density when compared to a lower one. This could be due to the engine performance being sub-optimal during cruise conditions, while an electric motor has an overall higher efficiency in this configuration, and because of the smaller mission factor, the battery weight is not as significant. Whether this result can be generalized to actual hybrid-electric aviation systems, requires further investigation.

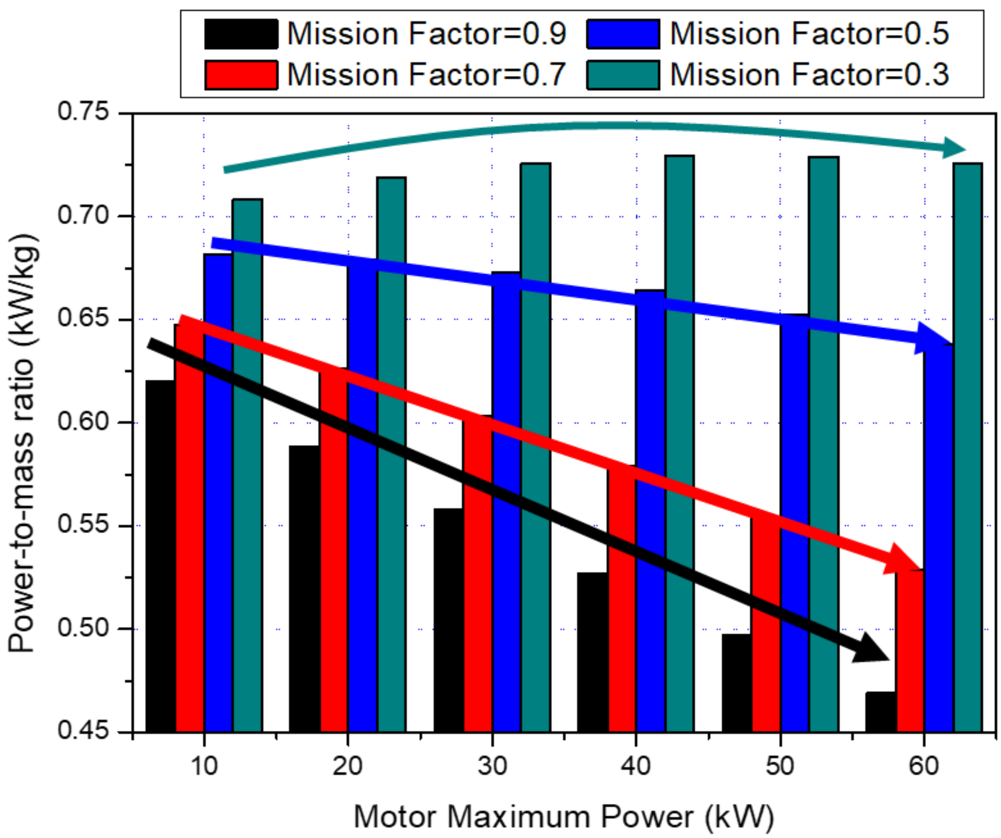

Figure 3-4: Power-to-mass ratio of hybridized system as a function of motor maximum power and fixed mission profile power output, without battery recharging.

Similar results are observed in Figure 3-5, but with the inclusion of using the engine to recharge the batteries. The mission factor of 0.7 case is considered, with varying degrees of recharging. It was observed that utilizing the engine to charge the battery allowed for a higher hybridization factor, at a higher fixed mission power output than without charging. Additionally, a longer charging period was more beneficial in increasing the power density than faster charging. A small difference is also observed for using a higher charging rate when compared to a lower one, while both having the same total charge time. For the higher hybridization factors (>60%), it appears that the engine cannot charge the battery at the higher charging rate. This could potentially be because the engine's power output is significantly reduced at this point, and there is not enough fuel to charge for the required amount of time. The current limitations in battery power and energy densities are the biggest drawbacks in hybrid-electric systems for aviation applications.

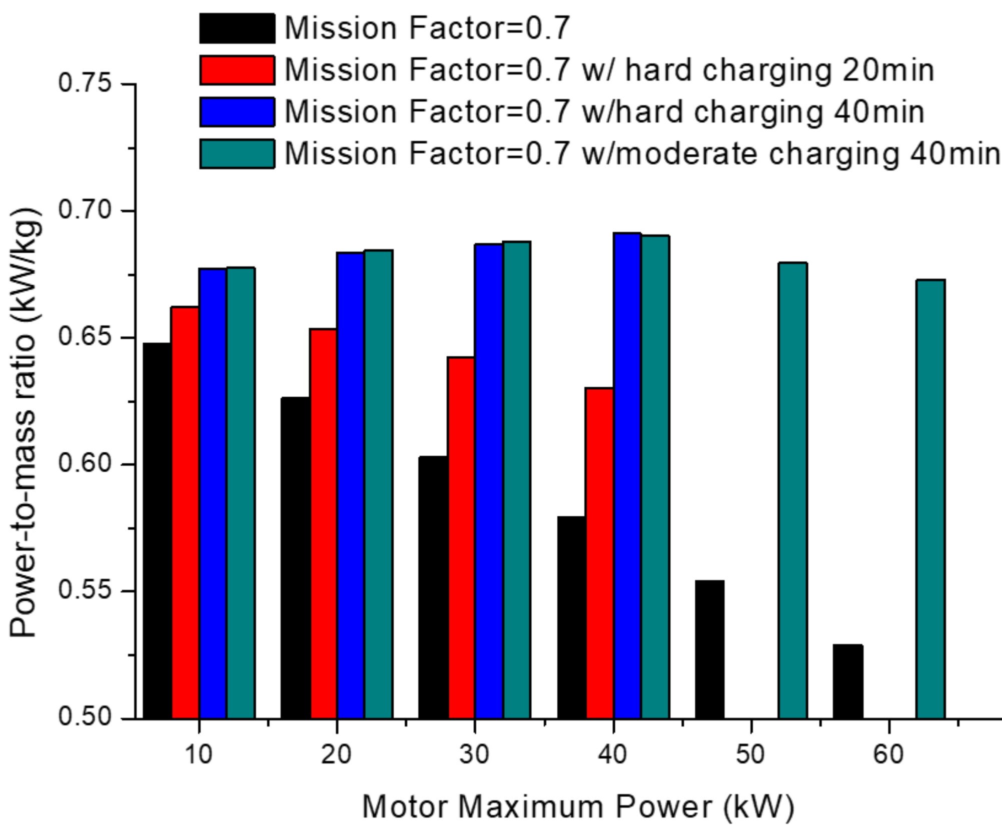

Figure 3-5: Power-to-mass ratio of hybridized system as a function of motor maximum power for a fixed mission profile power output of 0.7, with battery recharging.

3.0 CONCLUSION

In this work, a simplified zero order tool for sizing aviation relevant components was developed in Matlab/Simulink. The tool uses several input parameters which focus on the mission profile, engine performance, and electric motor/battery characteristics. The engine performance inputs were in the form of fuel consumption maps that were obtained from a higher fidelity engine model of 160 kW size, simulated in Ricardo Wave. The electric motor and battery were modelled using empirical relations from literature. The tool was run through a simplified case to observe the effects of changing the fixed power output, in the form of the mission factor, the hybridization factor and the recharging of the battery, on the overall power density. It was observed that an optimum hybrid configuration was only possible for a low load mission when there was no battery recharging. When recharging of the battery was allowed, optimization of the engine and electric motor operation at higher load missions was possible. The battery weight was the limiting factor in allowing higher degrees of hybridization.

4.0 FUTURE WORK

Future work will involve using more detailed inputs for the simulation, predominantly considering more aerodynamic effects and how they affect the power required during each phase of the mission profile, and in particular climbing and descent. A longer simulation cycle will be considered of about 10 hours, as well as requiring the aircraft to run only on the electric motor. The battery recharging cycles will be optimized and the model will determine the best time/case to recharge the battery. High fidelity simulation will be done for more engine types, to include the ability for the model to compare different engines during optimization procedures. Lastly, future efforts will be focused on developing a thermal management system for the aircraft that will allow the calculation of all heat generation and movement throughout the aircraft, in order to calculate the type of thermal management system required, as well as the weight it will add to the system.

5.0 REFERENCES

Deng, T., Lin, C., Luo, J. and Chen, B. (2018), "NSGA-II Multi-Objectives Optimization Algorithm for Energy Management Control of Hybrid Electric Vehicle" in Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, Vol. 233, No. 4, PP. 1023-1034.

Donateo, T., De Pascalis, C. L. and Ficarella, A. (2019), "Synergy Effects in Electric and Hybrid Electric Aircraft" in Aerospace, Vol. 6, No. 3, pp. 32-57.

Gur, O. and Rosen A. (2009), "Optimizing Electric Propulsion Systems for Unmanned Aerial Vehicles" in Journal of Aircraft, Vol. 46, No. 4, PP. 1340-1353.

Hung, J. Y. and Gonzalez, L. F. (2012), "On parallel hybrid-electric propulsion system for unmanned aerial vehicles" in Progress in Aerospace Sciences, Vol. 51, pp. 1-17.

Jansen, R., Bowman, C., Jankovsky, A., Dyson, R. and Felder J. (2017), "Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports", in 53rd AIAA/SAE/ASEE Joint Propulsion Conference in Atlanta, Georgia, 2017.

Meyer, D., Alexander, R. and Wang, J. K. (2017), "A simple method for energy otpimization to enhance durability of hybrid UAV power systems" in 2017 North American Power Symposium (NAPS), Morgantown, WV, pp.1-6.

Ricardo Software (2009), "WAVE 8.2 User's Manual".

Schömann, J. (2014), "Hybrid-electric Propulsion Systems for Small Unmanned Aircraft" in München, Techn, Univ., Diss.

Snyder, C.A., "Personal Rotorcraft Design and Performance with Electric Hybridization", 73rd American Helicopter Society (AHS) Annual Forum in Fort Worth, Texas, 2017.