Evaluation and Experimentation of Hybrid-Electric Propulsion Technologies for Unmanned Aerial Vehicles

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ABSTRACT

Against a background of rising fuel prices and an ever-increasing environmental concern, the aviation industry is transitioning to cleaner and more efficient alternatives to conventional propulsion systems. Hybrid electric propulsion systems (HEPS) offer several potential benefits including reduced fuel consumption, longer endurance, and can improve stealth characteristics of an aircraft by reducing its heat and noise signatures. The focus of this research is to theoretically and experimentally evaluate the performance of a parallel HEPS for use in small Unmanned Aerial Vehicles (UAV). A HEPS system was modelled parametrically to observe its theoretical performance relative to conventional UAV propulsion systems. Based on those results, the next objective was to combine all the individual components into a modular test bench to characterize performance and implement a rule-based controller. The modularity of the test bench allows each component to be exchanged to assess its impact on the system. The Electric Motor (EM) was able to supplement the power of the Internal Combustion Engine (ICE) to reduce fuel consumption, or act as a generator to recharge the batteries. Furthermore, the implemented controller reduced the overall fuel consumption of the HEPS when compared to its gasoline counterpart by running simulated UAV missions. Findings in this research will be beneficial to NATO operations by highlighting the major obstacles and challenges when building such a system. Finally, the results will open the door for future research work on the optimization and implementation of a HEPS on a UAV.

1.0 INTRODUCTION

A Hybrid Electric Propulsion System (HEPS) is defined as a combination of battery-powered Electric Motor (EM) and an Internal Combustion Engine (ICE). The design philosophy behind a hybrid electric propulsion system is to improve the efficiency of the overall propulsion system when compared to traditional fossil fuel powered solutions while providing a longer operating range compared to the alternative fully electric vehicles. However, the aforementioned benefits come with an increased complexity in the powertrain design together with the need of proper coordination between the different operating modes. This results in the need for an overall vehicle system control strategy that is significantly more complex. There are several possibilities of combining the ICE and the EM to form a HEPS. They can be grouped in two main configurations: series and parallel. In a series configuration, the ICE and the EM are not mechanically coupled. Instead, the engine is attached to a generator that can either directly power the motor or charge the on-board batteries. This means the ICE can be left to operate at its optimum torque and speed range, regardless of the driving conditions. However, as a series hybrid has multiple stages of energy conversion, it suffers from substantial losses (Kim, 1999), precluding its application in Unmanned Aerial Vehicles (UAV) (Harmats, 1999). On the other hand, parallel hybrid electric configurations couple the ICE and EM together through some form of mechanical coupling. This way, the power requirement can be fulfilled by either the sole action of each power unit, or a combination of the two as illustrated in Figure 1-1. This configuration is the main focus of this research.

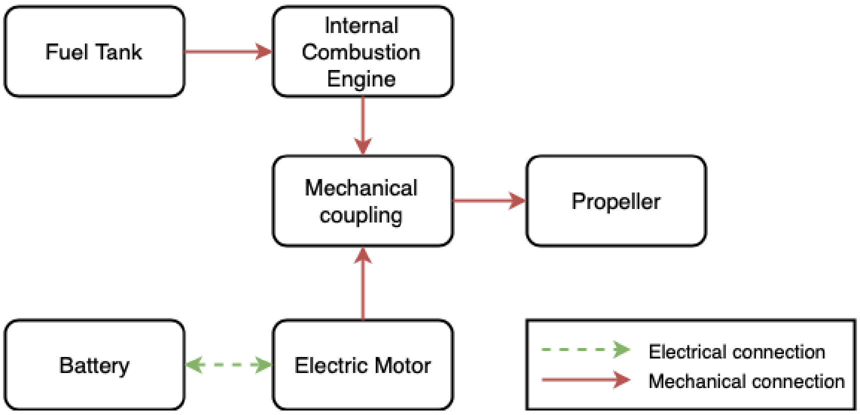

Figure 1-1: Hybrid Electric parallel configuration flow diagram.

There are four working modes for a parallel Hybrid Electric Vehicle (HEV) as described in Figure 1-2. *ICE ONLY* mode is represented by path 1. In this mode, the engine is the sole source of power to the aircraft. *REGEN* mode is depicted by path 2 and represents the regenerative braking mode where the ICE is used for both providing power to the propeller and also charge the on board batteries packs through the generator/motor. Another possible mode is *EM ONLY* as depicted by path 3, and is the pure electric propulsion mode. In this mode, the ICE is shut off or placed at idle while the EM fulfils the propulsion requirements. Finally, *DASH* mode is represented by the sum of path 1 and 3, where both power sources provide power to the propeller. This mode is typically used in high power-demand flight phases such as during take-off and climb to cruise flight segment.

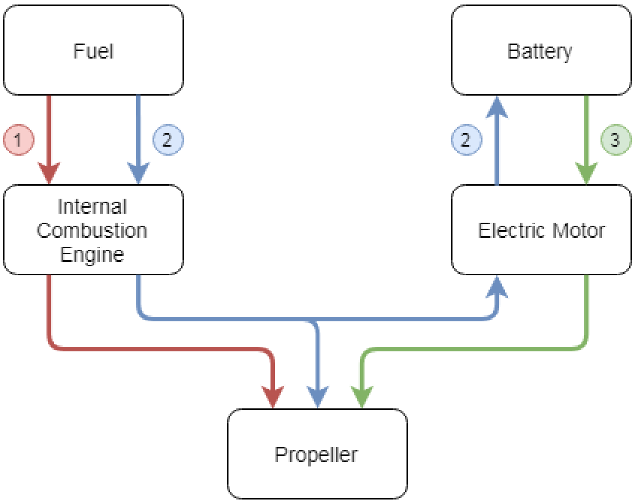

Figure 1-2: Energy paths on a Hybrid Electric parallel configuration.

The choice and design of a control strategy plays a crucial role in optimising Hybrid Electric Vehicle (HEV) technologies. A substantial amount of research has been conducted on HEV control strategies for automobiles but not many have been applied to UAVs. Conceptually, the simplest control strategy to implement is a rule based control strategy. This controller is simply composed by a set of rules that establish criteria for switching between different operational states. The Ideal Operating Line (IOL) concept would find its ideal application on such a control strategy as outlined by Hung et al. (2012). The IOL, also called ”economy line”, is a line made up of all the points which represent torque and speed combinations where the Brake Specific Fuel Consumption (BSFC) is minimal on different power lines for steady state conditions. Other approaches include using “*Fuzzy Logic Controllers”* (Karunarathne, 2008) and neural networks (Harmon, 2005).

2.0 THEORETICAL MODELLING

In order to analyze and compare the performance of a HEPS UAV, a theoretical model framework must be created to explore various types of architectures. With new groups contributing to the field of energy efficient propulsion systems for UAVs, it becomes difficult to make direct comparisons as there is a large range of applications. Each of the propulsion architectures must be built with unbiased models to compare against conventional UAV propulsion systems. Using Mathworks MATLAB, it was possible to model the aircraft dynamics independent of the propulsion system in order to conduct trade studies of the impacts on aircraft performance changing between architectures. In addition, each of the components of the propulsion systems were modelled parametrically in order to analyze the impacts of sweeping parameters to fully explore the design space. In this way, trade-offs can be evaluated to create a better understanding of the hybrid-electric architecture and drive engineering decisions.

Instead of comparing the steady-state operation performance of the various architectures, different mission profiles were created to evaluate how the theoretical models would perform in real world situations. Since UAVs are typically used in more than one type of operation, it is useful to analyze an architecture’s performance for a range of operating points and reduce bias.

An example mission that was evaluated is the “Pipeline Inspection” mission, in which the aircraft is commanded to follow a path’s terrain at a certain altitude, focussing on the aircraft’s ability to sustain various climb gradients and maximize endurance (Matlock, 2018). This mission features various operating conditions for the aircraft with steep climbs, slow descents and long cruise segments. One of the parameter sweeps conducted for this mission was sweeping the values for coefficient of lift (CL) from 0.55 to 0.90 to explore the impact of fuel burn. As can be seen in Figure 2-1, the performance of hybrid-electric architectures is favoured for higher CL values with a lower overall fuel burn mass, and the parallel hybrid architecture is consistently more efficient than the gasoline baseline.

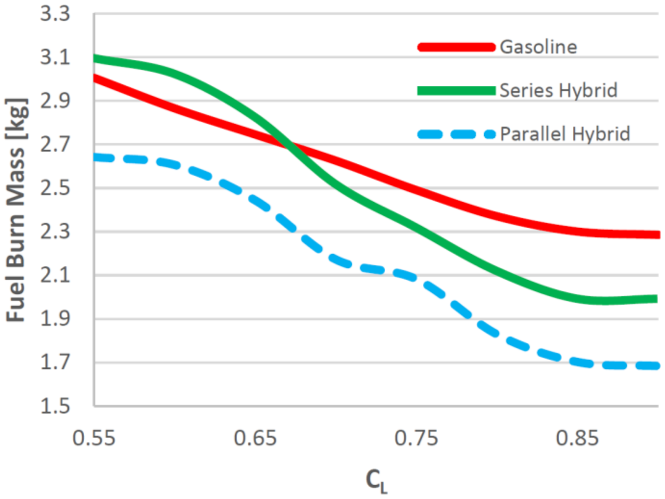

Figure 2-1: Framework design study example: Pipeline Inspection Mission CL versus Fuel Burn Mass. (Matlock, 2018)

For this mission type, an electric configuration would be unable to match the endurance capabilities of the gasoline or hybrid-electric configurations. With this framework, the performance of the UAV can be analysed to accurately estimate the amount of endurance it is capable of, and corresponding fuel requirements to determine remaining mass and volume availability for payloads. Furthermore, it provided valuable insight into the capabilities of a HEPS UAV, and proved this area of research is worth exploring in detail. The framework will aid in the development of a HEPS if the models are accurate as it will reduce the amount of experimental testing required. However, in order to validate the results generated in the framework, an experimental test bench was created.

3.0 IMPLEMENTATION

3.1 CONCEPT DEVELOPMENT

In order to experimentally evaluate and validate the performance of a HEPS, a prototype was fully designed, built and tested. The objective was to combine all the individual components of the HEPS into a test bench to characterize the performance of a parallel hybrid propulsion system, and to evaluate a rule-based controller based on the Ideal Operating Line concept for the control of the powerplant.

The ICE used in this project was a Desert Aircraft spark-ignited 35cc two stroke single cylinder engine. The maximum torque output of 2.99N·m occurs at full open throttle when the engine is running at around 5,500 RPM as depicted in Figure 3-1. For lower rotational speeds, the maximum torque available decreases substantially. Referring to Figure 3-2, there is a decreasing trend in BSFC with increasing throttle, and its minima is located between of 4,000 RPM to 6,000 RPM, and a torque from 1.7N·m to 2.0N·m.

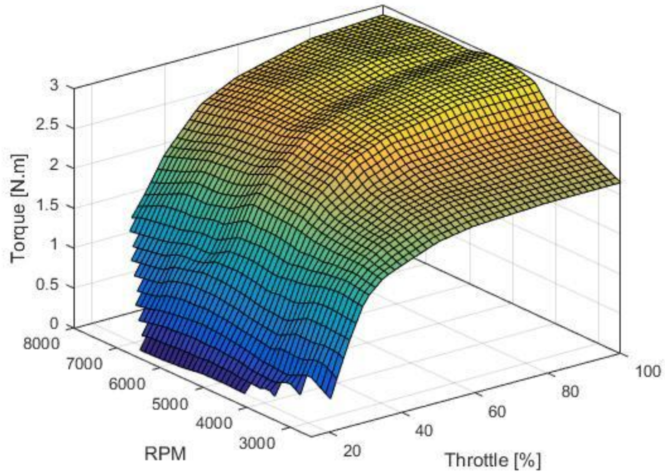

Figure 3-1: Torque as a function of throttle and RPM for the DA35.

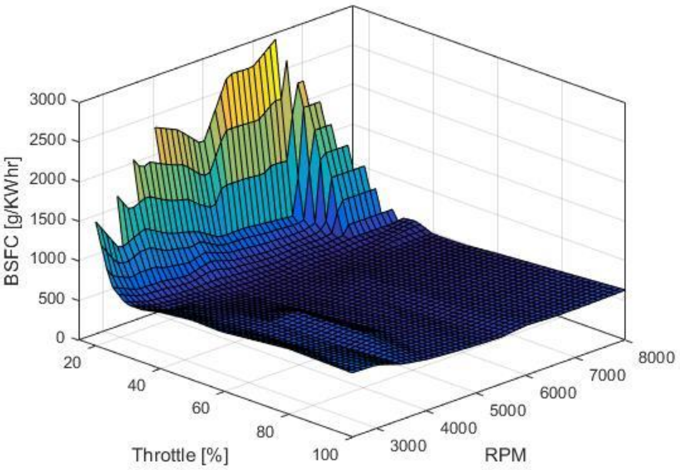

Figure 3-2: BSFC as a function of Throttle and RPM for the DA35.

A method of calculating the IOL of an engine consists of plotting lines of constant power on the BSFC map and then determining the minima along each isopower line for the lowest BSFC. It is possible to create an operating line that delivers the lowest BSFC for any given power range. Often the IOL points do not form a smooth line due to the limited number of data points available in the engine map as well as the very small fluctuations of fuel consumption in a rather large area. In order to obtain a workable IOL for this research, a smooth line was fitted through these points. In this case, a third order polynomial function was created for this line as shown in Figure 3-3.

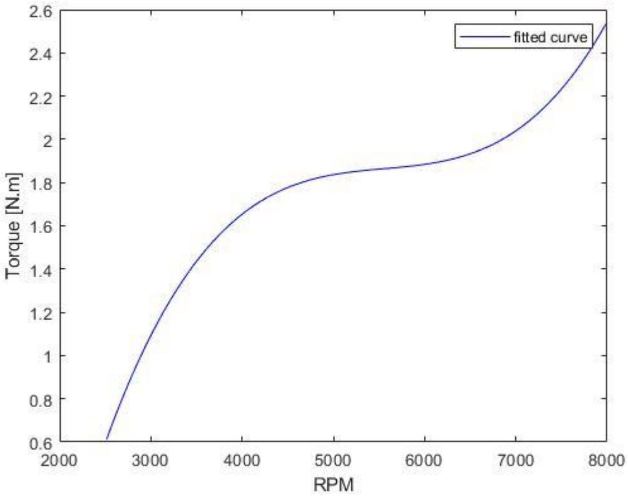

Figure 3-3: Ideal Operating Line of the DA35.

The electric motor used was an AXi 4130/20 GOLD LINE V2 outrunner brushless direct current motor. In Figure 3-4, it can be observed a maximum efficiency of 83% at 3,687 RPM with a decreasing trend above this RPM. This is an important fact because the HEPS under development will have the motor running at the same speed as the engine, meaning it will run at speeds up to 7000RPM, where it should be able to provide the requested torque to assist the engine.

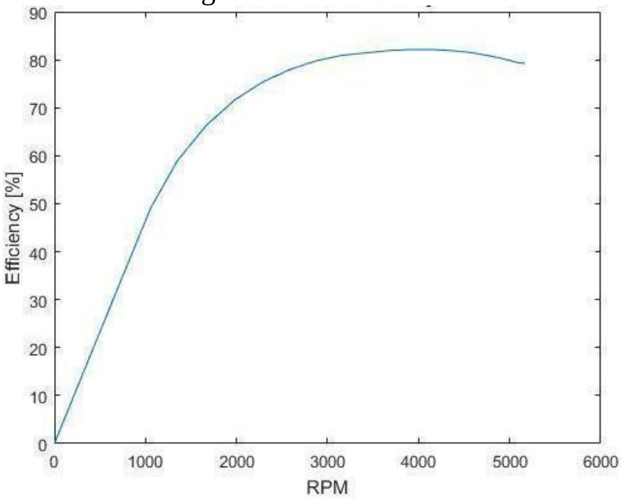

Figure 3-4: AXi 4130/20 efficiency test results.

The propeller selected for this project was a 19”x10 fixed pitch wood propeller. Several fixed pitch propellers were mapped during the electric motor test campaign and were plotted against the BSFC engine maps to foresee the possible working points of the system. The choice of propeller, and thus the load applied to the system, intended to provide a way of effectively testing the system.

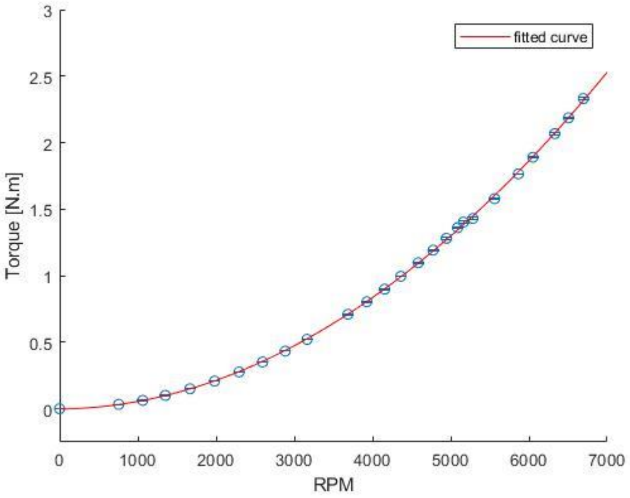

Figure 3-5: Torque versus RPM characteristic for the 19" x10 fixed pitch propeller.

Figure 3-5 shows the Torque versus RPM curve of this propeller. The experimental data (blue dots) was fitted with a second order polynomial curve (red) showing the torque follows a parabolic dependency with RPM, which corresponds to the theory (Glassock, 2012). A key component of a parallel HEPS is the mechanical clutch required to combine the power of the ICE and EM. There are two potential clutch mechanisms for a small hybrid electric UAV: an electromagnetic clutch, and a one-way bearing. The one-way bearing is cheaper, simpler, more reliable and lighter than the electromagnetic clutch making it a good choice for this proof-of-concept prototype HEPS. This was also the choice proposed in the studies reported by Koster (2011) and Greiser (2011).

3.2 CONTROLLER DESIGN

Hybrid Electric propulsion systems performance is highly dependent on the energy management system. The presence of an additional degree of freedom for satisfying the drive power demands implies that the performance of an HEV system strongly depends on the control of the power split. The design philosophy is to improve the efficiency of the overall system by operating each component at or close to its maximum efficiency region. In this research, efforts are mainly focused on optimising the engine operation to minimize fuel consumption. As stated before, a rule based control strategy is ideal for the type of controller intended. This was the selected method due to its inherent simplicity, highly predictive behaviour, and simple debugging. In this research, and given the experimental and proof-of-concept nature of this project, a previously developed controller by Harmon (2005) was used. This way, this research project represents a validation of the results presented in Greiser (2011) and Harmon (2005). The inputs to the particular system in question are a torque request and the system rotational speed. The controller then decides which power mode to use and the correspondent power split, according to the flowchart shown in Figure 3-6. The rule-based controller presented here is not a closed-loop controller, but it can have pseudo closed-loop behaviour with operator inputs.

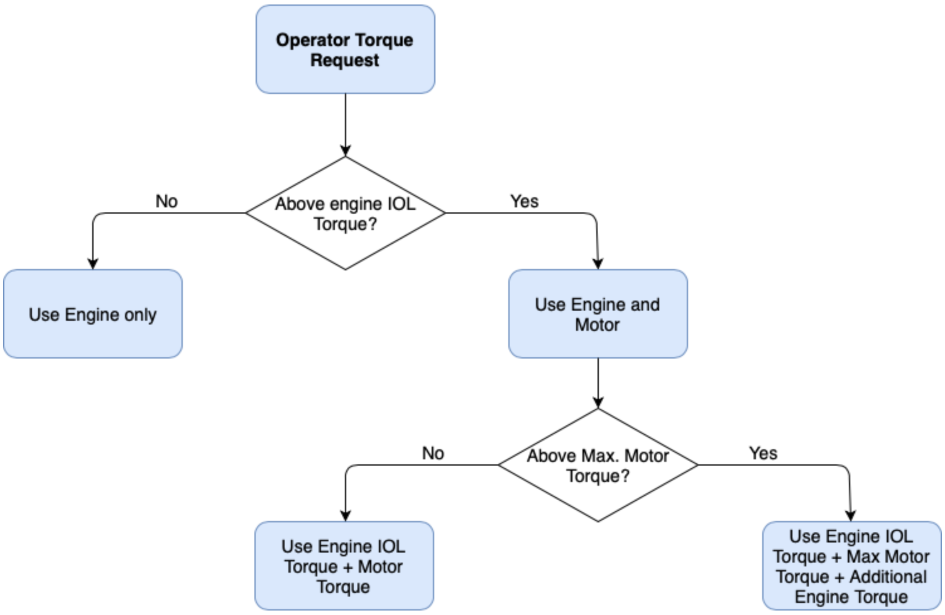

Figure 3-6: Parallel Hybrid Electric propulsion control system decision tree (Adapted from Greiser, 2011.)

Figure 3-7 illustrates the possible working points of the system, which can occur whenever a torque availability can equal a torque demand. Reducing the engine or motor throttle setting will reduce the respective available torque and the propeller RPM will settle at a lower level. This way, since a fixed pitch 19”x10 propeller is being used, the system is expected to always operate on this curve. Thus, conceptually and disregarding losses, the system is expected to only use the engine up to approximately 6,000 RPM. From that point onwards, an increase in torque request leads the engine to remain operating at its most efficient point while the motor contributes the rest of the requested torque.

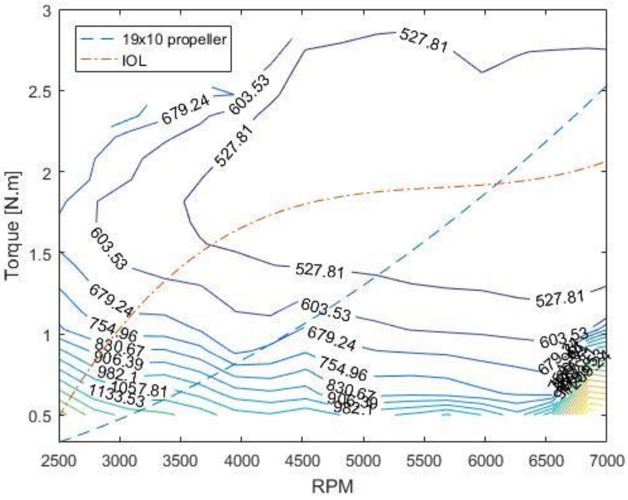

Figure 3-7: Propulsion System operating points with 19”x10 propeller and IOL.

The implemented controller has different modes it can operate under which are selected by the user. These embody the versatility of a hybrid system and offer the user different possibilities of operation depending on the mission requirements. The first is the *Single ICE Operation* mode. While a HEPS features both an EM and an ICE, the ICE provides the foundation of the propulsion system. The controller reads the torque request from the user and moves the ICE throttle valve accordingly. The second controller operating mode is the *Single EM Operation* mode which offers a quiet and low-vibration flight using the EM for propulsion while the ICE is set to idle. In this state, the one-way bearing will disengage given the lower rotational velocity of the engine. In a similar fashion to the *Single ICE Operation*, this mode reads the user input of required torque and sets the EM throttle accordingly. The third controller operating mode is the *Hybrid Operation* mode, where the controller optimises the operation of the ICE to minimize fuel consumption. It accesses look-up tables with the IOL information to continuously update the engine and motor operating points based on the requested torque and rotational speed. This mode is theorized to offer a lower fuel consumption when compared to the *Single ICE Operation* mode and is thus the main focus of this research project. Finally, the controller also features a *RESET* mode, which is the default mode the controller switches to whenever it is activated. The sole operation of this mode is to place the ICE at idle and to turn off the EM. This is an important safety feature as it allows for a safe and predictable behaviour when the controller is engaged.

3.3 EXPERIMENTAL SETUP

The parallel hybrid electric test bench was subjected to several iterations with many interactive phases. The first requirement of the test bench was for the design of a modular platform so that every component of the hybrid system could be switched with relative ease. This would allow for testing of any component combination of a parallel HEPS for small UAV applications. This also permits sensitivity tests to analyze how changing parameters affect the overall system performance. In addition, the test bench should be fully instrumented to collect all the required data to map the hybrid system performance and permit the controller operation. A schematic of the test bench mechanical design and sensor integration is presented in Figure 3-8.

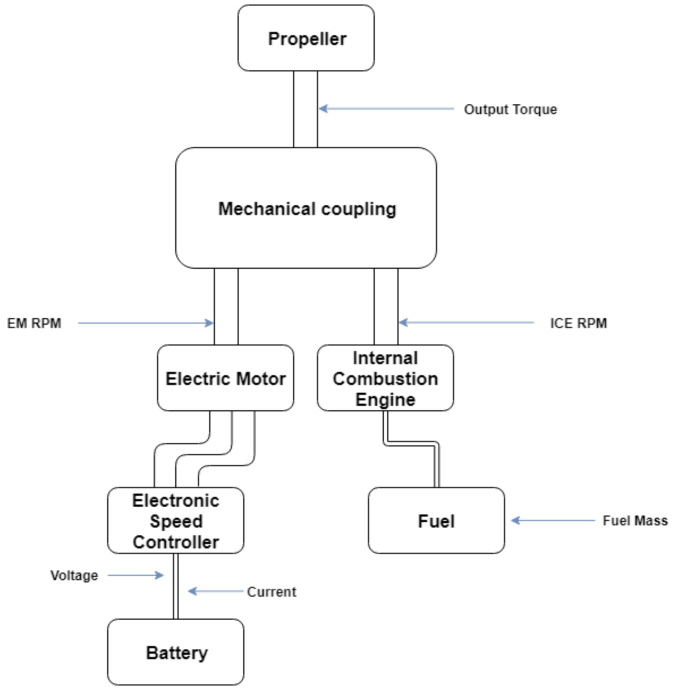

Figure 3-8: Parallel hybrid electric test bench schematic.

The sensor suite included the monitoring of several variables such as: voltage, current, rotational speed with hall effect sensors and fuel mass with a load cell. With the rotational speed of the propeller, the torque value is extrapolated from the experimental propeller test curves. These sensors allow for the control of the test bench and also assist in troubleshooting errors in the system. Their implementation is outlined in Figure 3-8. A simplified version of the Computer Aided Design (CAD) developed in the design of the test bench is shown in Figure 3-9.

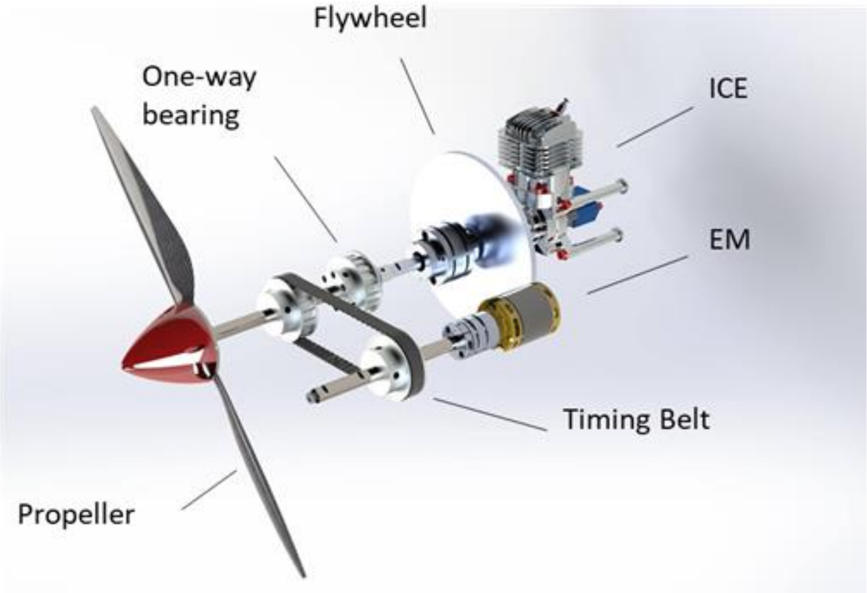

Figure 3-9: Detailed view of the parallel hybrid electric test bench CAD.

The engine crankshaft is connected to the one-way bearing through a flexible coupler designed to absorb engine vibrations. An aluminium flywheel is also attached to the crankshaft to increase the rotational inertia of the engine. The end of that shaft was inserted into the inner race of the one-way bearing assembly and locked by a metal pin (refer to Figure 3-9). A pulley was then machined to be embedded into the one-way bearing assembly as shown in Figure 3-10.

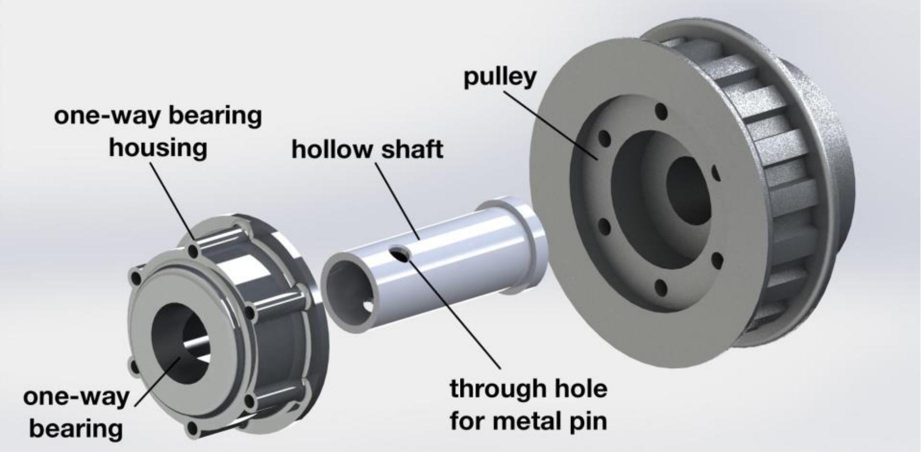

Figure 3-10: Custom one-way bearing assembly for parallel hybrid electric system.

Connected to the pulley of this assembly is a shaft that links directly to the propeller, as well as a second pulley that uses a timing belt to join the EM side of the transmission (see Figure 3-9). The propeller is located at the end of the shaft with a small step, and fastened with a nut. On the EM side, the motor is attached to the shaft through a flexible coupling to dampen torque spikes and negate minor misalignment. Both the EM and the propeller output shafts are supported by pairs of pillow blocks to maintain alignment. The final experimental integration of the parallel hybrid electric test bench can be seen in Figure 3-11.

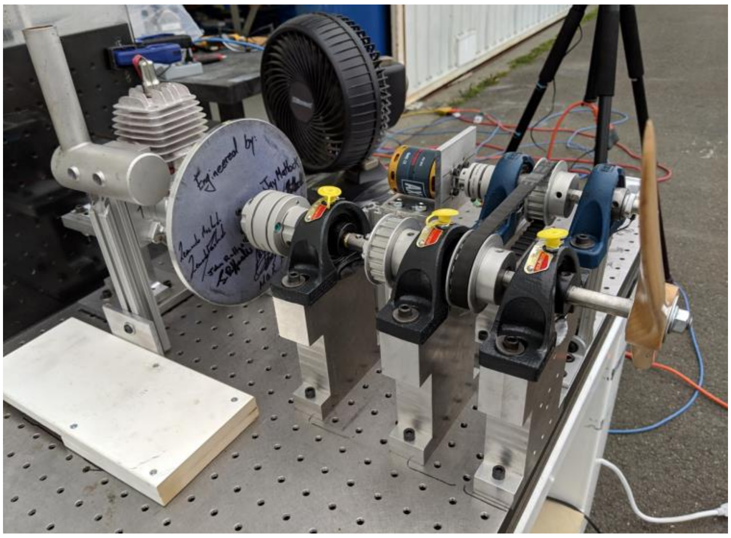

Figure 3-11: Parallel Hybrid Electric test bench.

4.0 RESULTS

4.1 SYSTEM CHARACTERISATION

The operational modes of the system as a whole are evaluated next. This test campaign is composed of four main tests: *EM ONLY*, *ICE ONLY*, *DASH* and *REGEN*. The purpose of the *EM ONLY* test was to map the performance of the electric motor on the hybrid powertrain. The test consisted of sweeping the EM throttle from 0% to 90% in steps of 5%, with the ICE disabled. Considering Figure 4-1, it is possible to verify a maximum efficiency of 71% at 3900RPM. Indeed, this is consistent with the component level experiments described in section 2, where the maximum efficiency was verified at approximately 3600RPM. The overall trend of the efficiency curves is comparable, however the approximate 10% difference in values can be attributed to powertrain losses due to friction in the system.

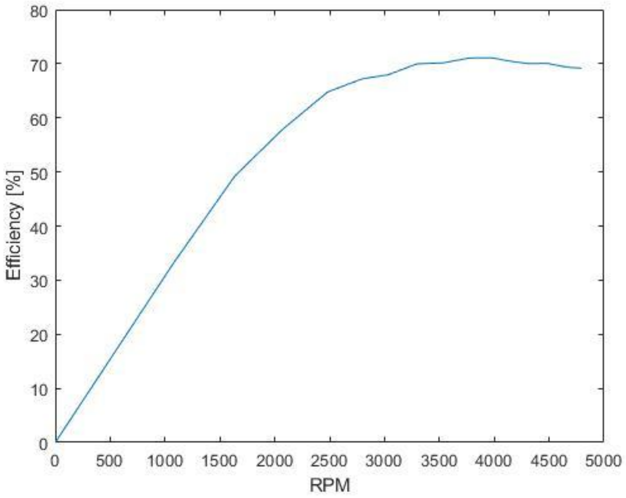

Figure 4-1: Efficiency results for the *EM ONLY* test.

Performance of the *ICE ONLY* can be analysed by monitoring the ICE fuel consumption, RPM and Torque output through several power demand sweeps. The test consisted of sweeping the engine speed from 4,000 and 7,000 RPM, a range that corresponds to the theoretical lowest fuel consumption. At each interval, the engine was tested for 5 to 10 minute to allow the engine to reach a steady state, and provide a large sample for a more accurate fuel flow calculation. During testing, it was found that the engine had difficulties running at lower RPM due to the friction of the system, but was able to run consistently and smoothly at higher RPM ranges. Referring to Table 4-1 the efficiency of the engine does not exceed 11% throughout the testing range, which is considerably lower value than the electric motor.

Table 4-1: Results for ICE ONLY tests on Hybrid test bench.

Speed	**Torque**	**Power$_{prop}$**	**Fuel flow**	**BSFC**	**η**
[RPM]	**[Nmx10^-3]**	**[W]**	**[g/min]**	**[g/KWhr]**	**[%]**
4760	1178.7	587.6	19.2	1955.8	4
5742	1708.4	1027.3	22.2	1293.8	6
6097	1924.2	1228.6	24.8	1211.6	7
6620	2265.4	1570.6	22.2	848.9	10
6691	2313.3	1620.9	23.2	859.6	9
6727	2338.3	1647.3	21.2	773.3	11

The objective of the *DASH* testing was to augment the power of the ICE with the EM and understand how the two power sources interact with each other when operating in tandem. The test consisted of keeping a constant ICE throttle, 40%, while sweeping the EM throttle from 0% to 60% in steps of 10%. It is possible to see through the change in RPM (illustrated in Figure 4-2) that this mode functions as expected. Indeed, the motor is able to assist the engine in its operation. Furthermore, the clutch system successfully combines the power of these two power sources despite the intricate mechanical interaction. This test also indicated that the EM never manages to completely overrun the ICE during dash mode. Therefore, if the ICE remains at idle during electric only mode operation, it will still provide power to the system.

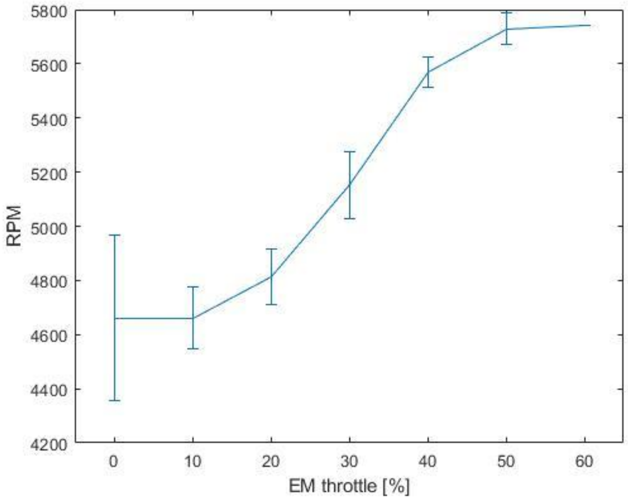

Figure 4-2: RPM results for the *DASH* test.

Figure 4-2 shows the RPM measurements with indication of the standard deviation between tests. These results show a decreasing slope on the high end of the throttle. This was an unexpected behaviour and possibly is attributed to the high rotational speeds where the motor is no longer able to operate effectively. A possible solution to this problem would be to install a different gear ratio between the motor and engine pulleys allowing the rotational speed perceived by the motor to decrease, enabling it to work at a lower speed, and thus more effectively.

Table 4-2: Detailed results for DASH operating mode.

ICE_{thr}	EM_{thr}	$\Delta Torque_{prop}$	$\tau_{EM} = \frac{I - I_0}{K_v}$	$\Delta Power_{prop}$	$Power_{bat}$	$\frac{\Delta Power_{prop}}{Power_{bat}}$ [%]	$\frac{\Delta Power_{prop}}{Power_{prop}}$
[%]	**[%]**	**[Nmx10^-3]**	**[Nmx10^-3]**	**[W]**	**[W]**	**[%]**	**[%]**
40%	10%	0.2	50	0.1	73.0	0.2	0.02
	20%	75.2	193	56.2	179.2	31.4	10.2
	30%	247.5	358	191.6	306.9	62.4	31.5
	40%	477.1	513	385.7	423.2	91.1	51.9
	50%	569.5	588.	467.9	477.7	98.0	49.9

Tables 4-2 highlights the influence of the EM action on the system performance. The variables $\Delta Torque_{prop}$ and $\Delta Power_{prop}$ indicate the change in torque and power, respectively, relative to 0% EM_{thr}, as we increase the throttle value. Assuming a constant engine output torque, the results of $\frac{\Delta Power_{prop}}{Power_{bat}}$ suggest that the higher the throttle value, the more efficiently the motor can provide power to the system and assist the engine. This is also indicated by the increasing slope in Figure 16, along with the degree of hybridization ($\frac{\Delta Power_{prop}}{Power_{prop}}$) that also presents a growing trend.

The *REGEN* aimed to investigate the regenerative braking working mode and create a better understanding of the system behaviour when the motor acts as a generator. Opposite of the *EM ONLY* mode where power is consumed from the batteries, the regenerative braking mode withdraws power from the engine to charge the batteries. The test consisted of keeping a constant ICE throttle, 60%, while sweeping the EM throttle from

0% to −90% in steps of 10%.

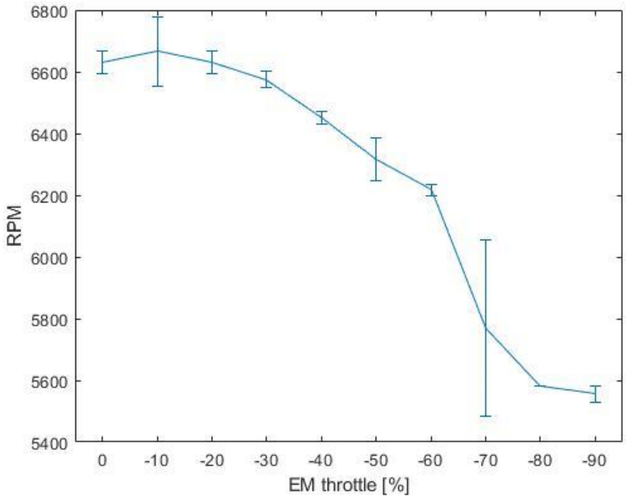

Figure 4-3: RPM results for the *REGEN* test.

Figures 4-3 and 4-4 present the rotational speed and current measurements of the EM respectively. The negative sign in the measured current indicate that it is flowing into the batteries, charging them. Furthermore, there is an increasing negative slope of the RPM with a sharp decrease near −70% throttle. This can be explained by the increasing load on the engine that caused the engine to set at a lower RPM. The current presents an approximately linear and constant decrease, reaching a maximum value of −12.8A.

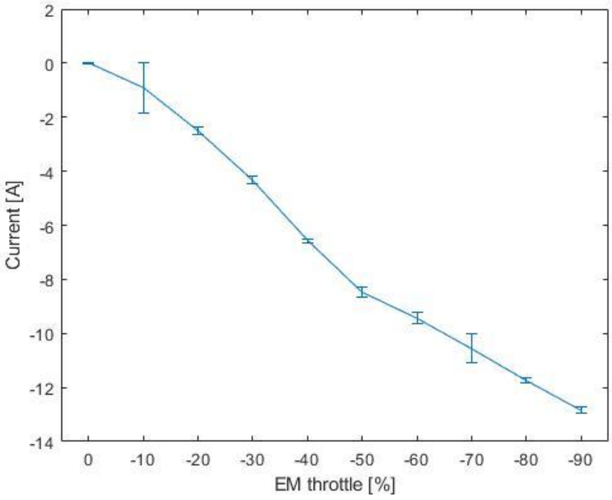

Figure 4-4: Current results for the REGEN test.

4.2 CONTROLLER PERFORMANCE

In this section, the developed controller is tested. The test campaign involved evaluating the system response to several step functions as well as investigating its dynamic response to changing inputs. Thus, each mode was tested separately through a sample mission consisting of three different portions with different “Torque Request” values found in the system’s normal operation. The test campaign was composed of three controller operating modes: *Single EM Operation*, *Single ICE Operation* and *Hybrid*
Figure 4-5 depicts the *Single EM Operation* mission profile plotted in blue with the propeller torque

results in orange. It shows a highly constant motor behaviour, with negligible torque spikes. This facilitates the controller design and suggests that the mapping of the Torque-Throttle curves closely depict the system behaviour.

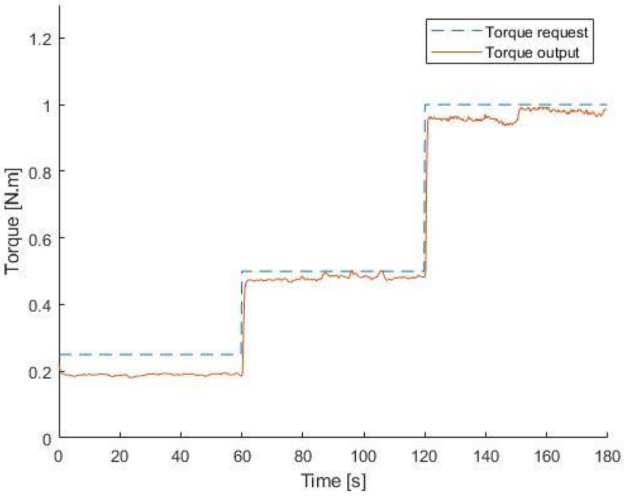

Figure 4-5: Propeller torque during *EM Single Operation* mission.

Figure 4-6 depicts the *Single ICE Operation* mission profile plotted in blue with the propeller torque results in orange. It is possible to observe that for the first portion of the mission, the measured torque is close to the requested one, meaning a successful mapping of the Torque-Throttle curve for this specific operating point. The same is not verified for the last two portions of the mission where the values drastically differ.

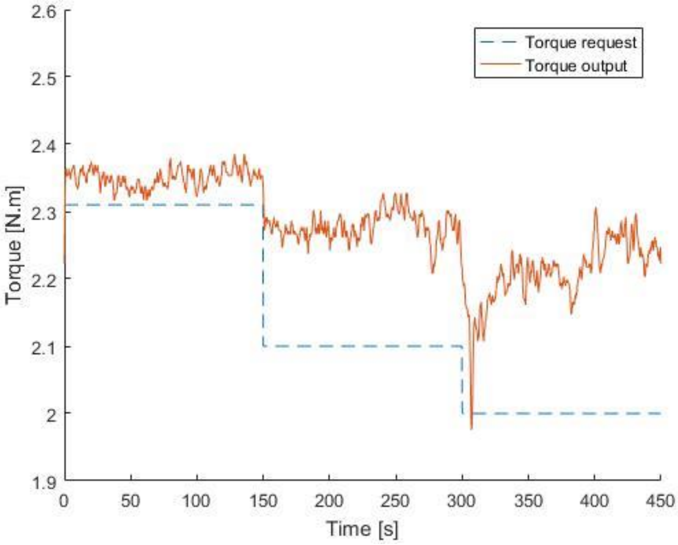

Figure 4-6: Propeller torque during *ICE Single Operation* mission.

The RPM measurements present an identical trend given the torque measurement method used. The overall signal is highly noisy as a result of the torque spikes during the engine operation. It is possible to see that the irregularities and spikes increase in amplitude as the rotational speed is reduced. In fact, near the end of the second portion of the mission, large variations in rotational speed are verified with a severe drop in RPM when the system transitions to the last mission segment, where it presented a very unstable behaviour. This illustrates the difficulties in controlling such a power unit, where it is difficult to predict its torque output, in addition to the challenges raised by its unsteady nature. Table 4-3 contains the different fuel consumption rates in each section of the mission as well as the overall fuel consumption. It shows a similar fuel consumption trend compared to the first two sections of the mission, while presenting a clear reduction in fuel flow in the last portion, due to the lower rotational speed and throttle value.

Table 4-3: Fuel consumption results for *ICE Single Operation* Mission.

Mission Segment	Fuel Flow [g/min]	Fuel [g]
1	24.50	61.15
2	24.62	61.45
3	22.62	56.46
Entire Mission	23.91 (average)	179.06 (total)

In order to directly compare the controller performance between the *ICE Single Operation* and the *Hybrid Operation*, the same mission profile was used for this test.

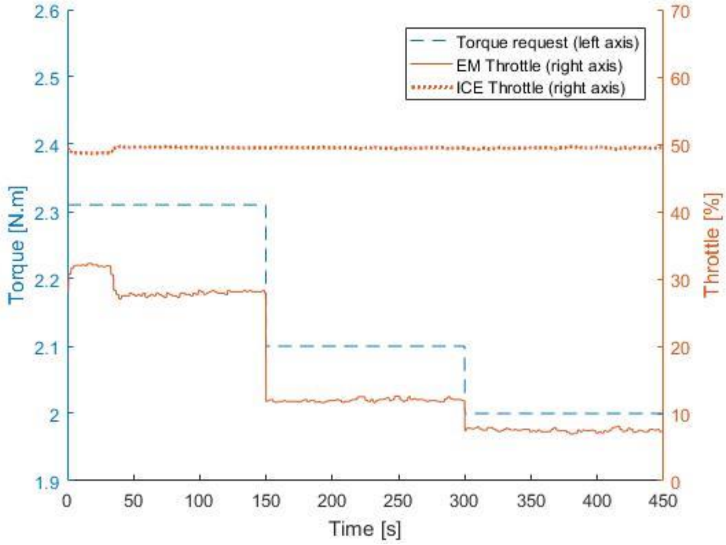

Figure 4-7: Throttle variation for *Hybrid Operation* mission.

Figure 4-7 presents the throttle percentages of both the EM and the ICE. It is possible to see that the controller behaves as expected and tries to optimize the efficiency of the system while placing it in a state where it would output the requested torque. When the controller is engaged, it reads the rotational speed and calculates the required torque output of the engine, in order to operate it at its most efficient point. The electric motor is responsible for making up the difference between the engine torque and the requested torque. From Figure 4-8, in this initial segment, a positive current flow is visible meaning the motor is successfully providing torque to the system. After an initial period where the rotational speed remains approximately constant, the system accelerates without any change to the throttle position. Thereafter, the controller again calculates the optimum torque output for the engine and sets the correspondent throttle position. However, for this rotational speed the motor is no longer able to contribute significantly to the output torque, and the current value is low at 0A.

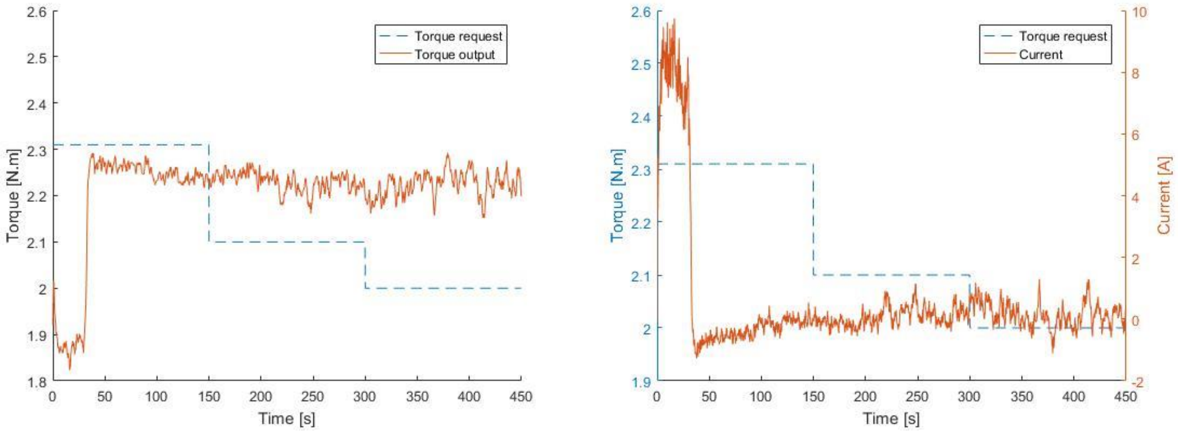

Figure 4-8: Propeller torque results (left) and battery current results (right) for *Hybrid Operation* mission.

Given the interaction between mechanical, electric and power electronics components in this system, it is an observation that requires further investigation. Given the high rotational speeds, the back electromotive force generated might surpass the difference in potential the electronic speed controller sets at that specific throttle positions and thus the current starts flowing in the opposite direction. During the remainder of the mission, the system shows an insensitivity to the input Torque Request, despite the change in EM throttle setting, and continues to operate at roughly the same rotational speed. The correspondent torque is always higher than the requested one. Table 4-4 shows the fuel consumption data. It indicates a constant fuel consumption rate, due to the near constant rotational speed and engine throttle value. There is a 3% reduction in fuel consumption relative to the ICE Single Operation mission. Nevertheless, it is important to emphasize that the observed torque output values were different.

Table 4-4: Fuel consumption results for *Hybrid Operation* Mission.

Mission Segment	Fuel Flow	Fuel
	[g/min]	[g]
1	23.24	58.01
2	23.35	58.19
3	23.26	58.07
Entire Mission	23.28 (average)	174.27 (total)

5.0 CONCLUSION

This research successfully proved the feasibility of a HEPS for small UAV. Work in this research began with the theoretical modeling of a HEPS, including the individual components, in order to observe the design trade offs. The theoretical results of the framework motivated further exploration and thus the development of a test bench which featured a parallel architecture with representative components of a small UAV. This test bench was fully instrumented in order to adequately control the system, as well as collect data on its performance.

A comprehensive test campaign allowed to fully map each of the four system operating modes. The results found in this research proved that the system is reliable, safe and is able to enhance the versatility of a UAV by providing it with a range of different operating points.

In addition, a supervisory controller was implemented that automatically drives the system based on the current operating mode, the system rotational speed and the user torque request. The controller offers three different operating modes, *Single ICE Operation*, *Single EM Operation* and *Hybrid Operation*. It allowed for the evaluation of the systems dynamic behaviour to changing inputs as well as its open-loop response to a step function. The main challenges of designing, implementing and controlling a HEPS were assessed and provided insight on how the two power units interact with each other.

For future research, the designed test bench provides a facility to further explore and validate other control strategies. In addition, by changing the system components makes it possible to evaluate their effect on the overall system performance.

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