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DelftaCopter Propulsion Optimization from Hover to Fast Forward Flight using Windtunnel Measurements

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ABSTRACT

Enlarging the flight envelope of aircraft has been a goal since the beginning of aviation. But requirements to fly very fast and to hover are conflicting. During the design of the DelftaCopter, a tail-sitter hybrid UAV with a single large rotor for lift in hover and propulsion in forward flight, the design of the rotor needs to properly balance hovering requirements and fast forward flight requirements. The initial design with a one meter rotor placed too much emphasis on efficiency in hover, while most flights consist of very short periods of hover and very long phases of forward flight. Two new rotor designs and corresponding motors were tested in an open jet wind tunnel. The propulsion system was tested from hover conditions to very fast forward flight in search of the most optimal operating point for each condition. The resulting system requires merely more power than the initial rotor in hover while it is capable of much faster forward speeds. The power requirements are shown to be compatible with modern power sources like Lithium-Ion batteries, which form the next step in improving the efficiency of hover-capable fast UAV.

1 INTRODUCTION

Extending the flight endurance and flight range of aircraft has been a goal since the beginning of aviation. This has typically been solved by increasing the size of aircraft to carry more fuel. But as Unmanned Aerial Vehicle (UAV) were gaining in popularity, this has re-triggered the quest for small and efficient platforms. Many real-life applications have a combined need for long range but also vertical take off and landing [1, 2]. Unfortunately these requirements are conflicting.

Hybrid UAV have been proposed to address the combined needs of long range and hovering capability [3]. By using a hovering set of rotors, vertical take off and landing capability was added to an efficient fixed wing airframe, which enables long range flights [4].

To further optimize the efficiency, a single rotor is more efficient than several smaller rotors. The DelftaCopter¹ is a platform that uses this approach. Using collective pitch, the rotor can be reconfigured for optimal hover and optimal fast forward flight. Nevertheless, finding the combined optimum of hover and forward flight remains a challenge as for hover an as large as possible rotor would be desired for efficiency, while for forward flight at high speeds, a much smaller propeller is optimal [5]. To assess the efficiency, several rotors are tested in windtunnel and subsequently in forward flight.

Section 2 presents the windtunnel measurements. Section 3 gives the results of the outdoor test flights. Finally, Section 4 gives the conclusions.

2 WINDTUNNEL



Figure 1: The new DelftaCopter Propulsion System is mounted on a static test rig in the TUDelft Open Jet wind-tunnel. The test setup includes force measurements, moment measurements, voltage, current, airspeed, rotor pitch, throttle and rotor rpm measurements.

Windtunnel measurements were performed in the TUDelft open jet windtunnel. A rotor system was mounted on a static rig in front of the opening as shown in Figure 1. The rotor was placed on a RC-Benchmark Series 1780 force

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¹<http://www.delftacopter.nl/>



Figure 2: Close up of the new rotor blades (left), the force and moment balance (middle) and the airspeed probe (on top). The windtunnel blows from left to right.

and moment measuring device². The balance not only logged forces and moments but also logged total current consumption, voltage and Rotations Per Minute (RPM). A pitot tube was recording the local air speed, which can be seen in Figure 2. Onboard measurements were performed onboard a Paparazzi-UAV [6] autopilot board. The measurements included RPM, Voltage, Airspeed, Current reported by the Electronic Speed Controller (ESC), Throttle commands and Collective pitch commands. Two separate logfiles were obtained, namely one from the balance and one from the autopilot. The logs were then synchronized by aligning the measurements that were obtained by both, namely the RPM and the current.

The autopilot was programmed to systematically step through its entire pitch and throttle range as illustrated in Figure 10. The whole process was repeated for two sets of rotor blades, namely the 24inch and 26inch blades from *T-Motor*. Several combinations of airspeed, throttle and pitch lead to destructive combinations, being it either due to over-RPM, over-current, over-temperature or any RPM that would make the setup vibrate excessively. Therefore, the range of pitch and throttle values were manually limited to safe conditions. For every pitch, throttle, rotor and airspeed combination, the autopilot would wait 3 seconds for the RPM, Current and flow to stabilize. An automated analysis tool in *MATLAB* then averaged the values during the steady phase only, which is shown as red crosses in Figure 10.

Figures 11 show the obtained net thrust for various throttle and collective pitch settings and various airspeeds. The required power to obtain this thrust is shown in Figure 12. Finally, Figure 13 shows an estimation of the obtained effi-

ciency³.

3 TEST FLIGHTS

3.1 Power in function of RPM



Figure 3: Take-off of the DelftaCopter PH-3MM during an outdoor test-flight.

To validate the figures found in the wind tunnel tests, outdoor test flights are performed. A DelftaCopter was registered under the Dutch CAA-NL as *PH-3MM* and is shown in Figure 3. The UAV was flown at a variety of throttle levels and collective pitch values, and the resulting airspeed and power are then used to find the optimum.

Figure 4 shows the decreasing RPM as the collective pitch is increased and the throttle decreased while the airspeed is kept relatively constant. Figure 5 shows the relation between throttle, collective pitch and rotor RPM that leads to a constant airspeed of about 22 m/s.

The required power to fly at this airspeed depends on rotor RPM and is shown in Figure 6. It can clearly be seen that lower RPM are more efficient as the power used ($P = U \cdot I$) of lower to fly at the same airspeed ($P = V \cdot Drag$).

3.2 Power in function of speed

A second test flight was performed at varying airspeed. The power required in function of the airspeed is shown in Figure 7. The third power fit ($P = f(V^3)$) is shown in red.

The track that was flown is shown in Figure 8. Notice the increasingly large turn radius as the airspeed increases while the DelftaCopter makes turns with a limited bank angle that is maxed out during most of the turn.

The raw airspeed and current in function of time is given in Figure 9. In the time frame from 20 to 30 minutes into the flight, the speed was increased. The hovering phases are

²Max thrust: 25 kg, max torque 12Nm, max voltage 60V, max current 100A continuous and 150 burst.

³This value is highly influenced by the accuracy of the current and force calibrations.

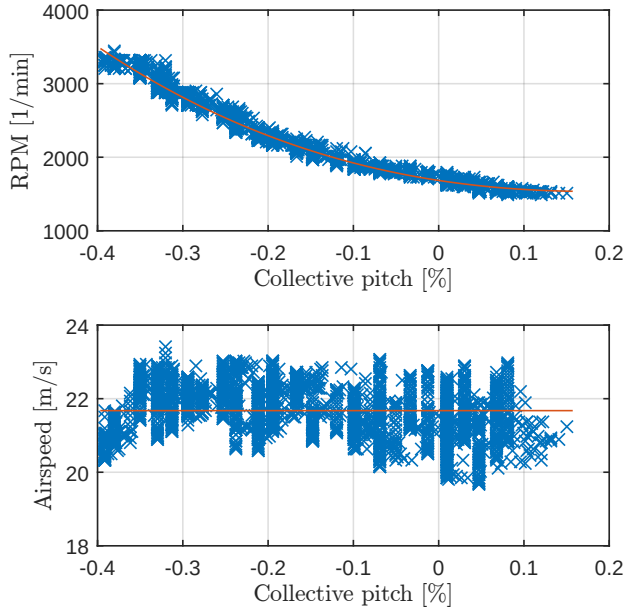


Figure 4: RPM in function of collective in forward speed for a constant airspeed.

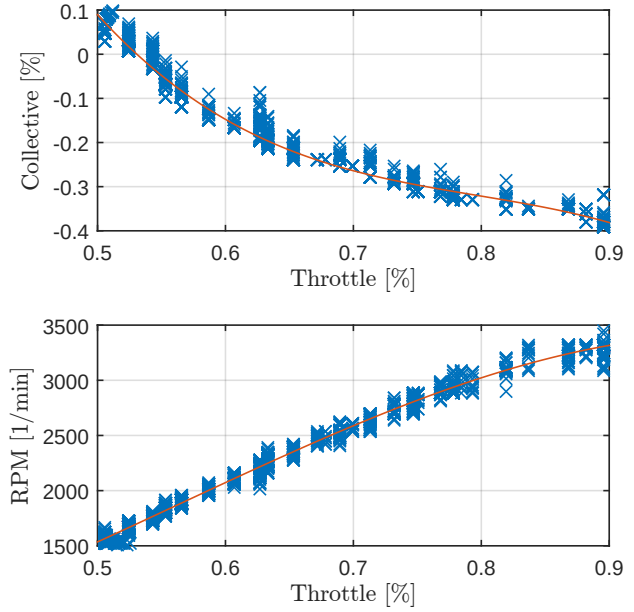


Figure 5: RPM in function of collective in forward speed for a constant airspeed.

clearly recognizable as the airspeed drops to zero while the used current increases to over 25Amp .

3.3 Trade-off between 24 inch and 26 inch rotor

A significant difference in efficiency in forward flight could not be found at speeds below 25 m/s . During hover, however, a very significant difference was observed. The motor and rotor combinations can still hover with much lower battery voltages. To increase the range of the **DelftaCopter**, Lithium-Ion batteries are used that provide low discharge rate and show significant voltage drops when loaded at the limit.

With the 24 inch (61cm) rotor, **DelftaCopter** could only empty its battery 70% while still being able to hover. Using the larger 26 inch (66cm) rotor, **DelftaCopter** could empty its battery to 90% before the voltage drop would make it impossible to hover. This is due to the higher voltage drop of the battery by the higher load of the less efficient smaller rotor on the one hand, and because of the higher voltage needed by the motor to reach a higher RPM on the other hand. This significant difference of 20% was deemed more important than the slight increase in forward flight efficiency.

3.4 Comparison with 2016 rotor design

The 1m diameter rotor 2016 **DelftaCopter** could hover using significantly less power than the new 66cm (26 inch) rotor. But in forward flight however, the opposite is true. Since **DelftaCopter** spends way more time in forward flight than in hover, overall the smaller rotor yields a huge boost in range.

The smaller rotor and motor with more torque also has

indirect advantages. Upon stall for instance, the rotor picks up RPM much faster when switching to hover mode. This allows the new **DelftaCopter** to recover from much more dramatic situations.

The smaller rotor also has complications. The control is further away from helicopter control. This is the topic of a different study.

4 CONCLUSION

A new propulsion design for the **DelftaCopter** was tested in the Open Jet Windtunnel Facility (OJF) wind tunnel and subsequently in real test flights. The wind tunnel measurements have shown that the rotor can be efficient over a wide

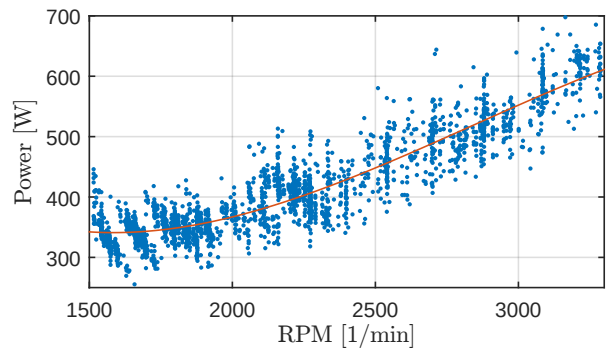


Figure 6: Power required to fly a 22 m/s at various RPM.

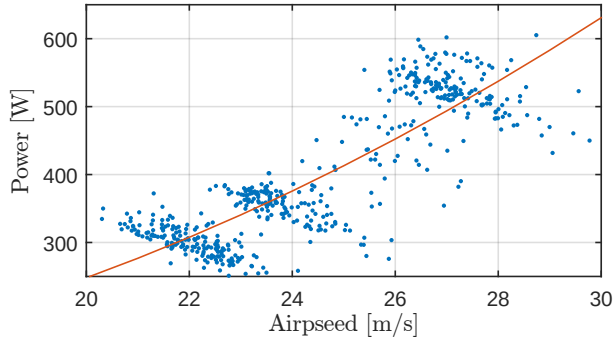


Figure 7: Power versus airspeed during outdoor test flight.

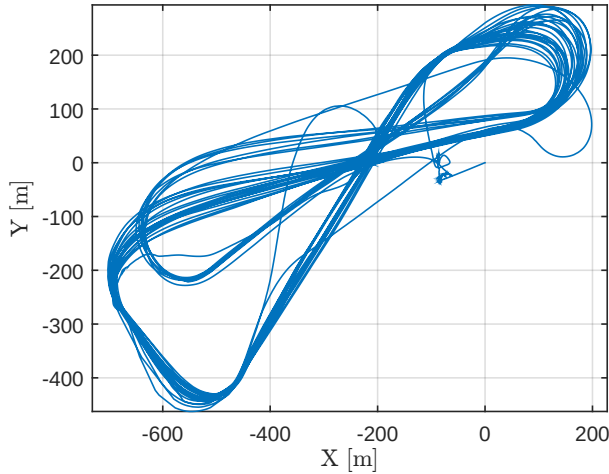


Figure 8: Top view of the track of the 50 minute test flight.

range of RPM. The optimal RPM for a given situation could be obtained and subsequently used in outdoor test flying. Since no accurate drag of the fuselage was measured in the windtunnel, real performance data was obtained from outdoor testing in real world conditions. While noise levels in the outdoor measurements are high, nevertheless, accurate performance data was obtained. The new 2018 **DelftaCopter** rotor and motor performance is compared with the 2016 **DelftaCopter** rotor design. The efficiency at high speed is shown to be dramatically improved, while hovering capabilities are not compromised. Overall the capabilities of the **DelftaCopter** were highly improved.

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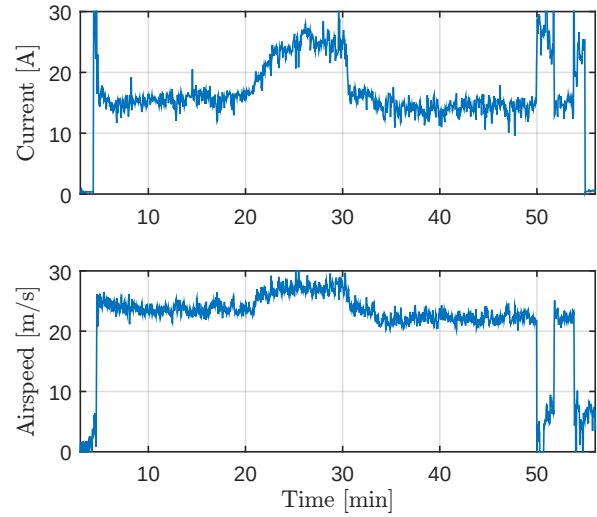


Figure 9: Used current of the 6-cell Li-Ion battery.

	2016	2018
Rotor diameter	100 cm	66 cm
Power in hover	≈ 600 Watt	≈ 700 Watt
Power in forward flight at 20 ms	≈ 400 Watt	≈ 260 Watt
Maximum forward speed	≈ 21 m/s	≈ 28 m/s

Table 1: Comparison between the 2016 and 2018 **DelftaCopter**.

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APPENDIX A: PLOTS

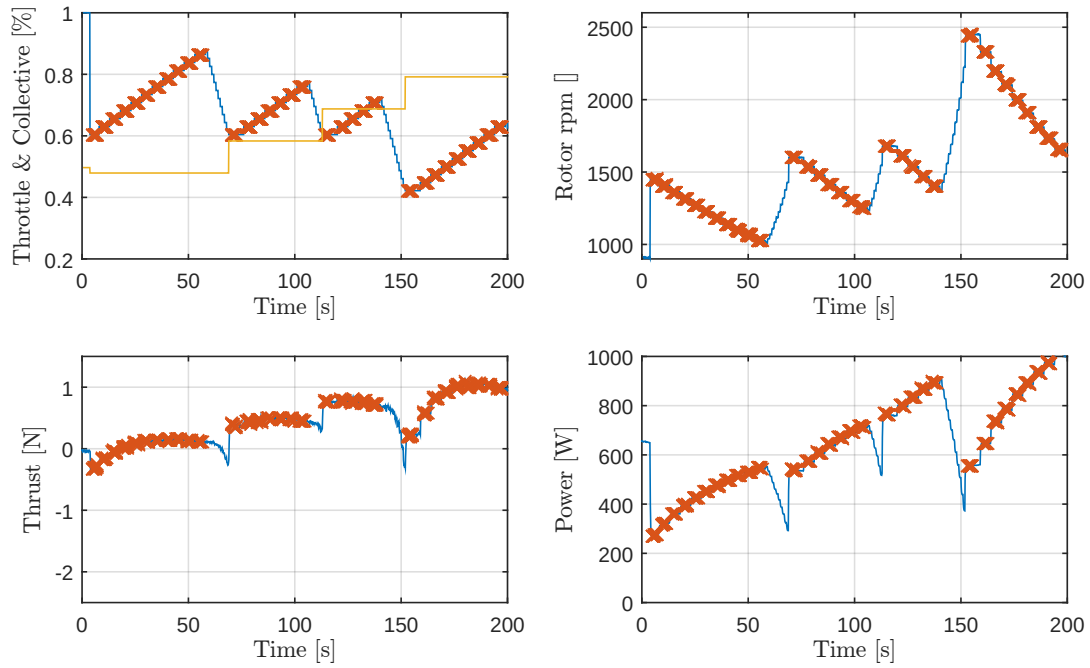


Figure 10: A fragment of a time series obtained from the OJF wind tunnel testing. The autopilot commands an series of pitch and throttle settings for 3 seconds each. Once everything is stabilized, the average over 1.5 seconds of measurement is taken (Red X).

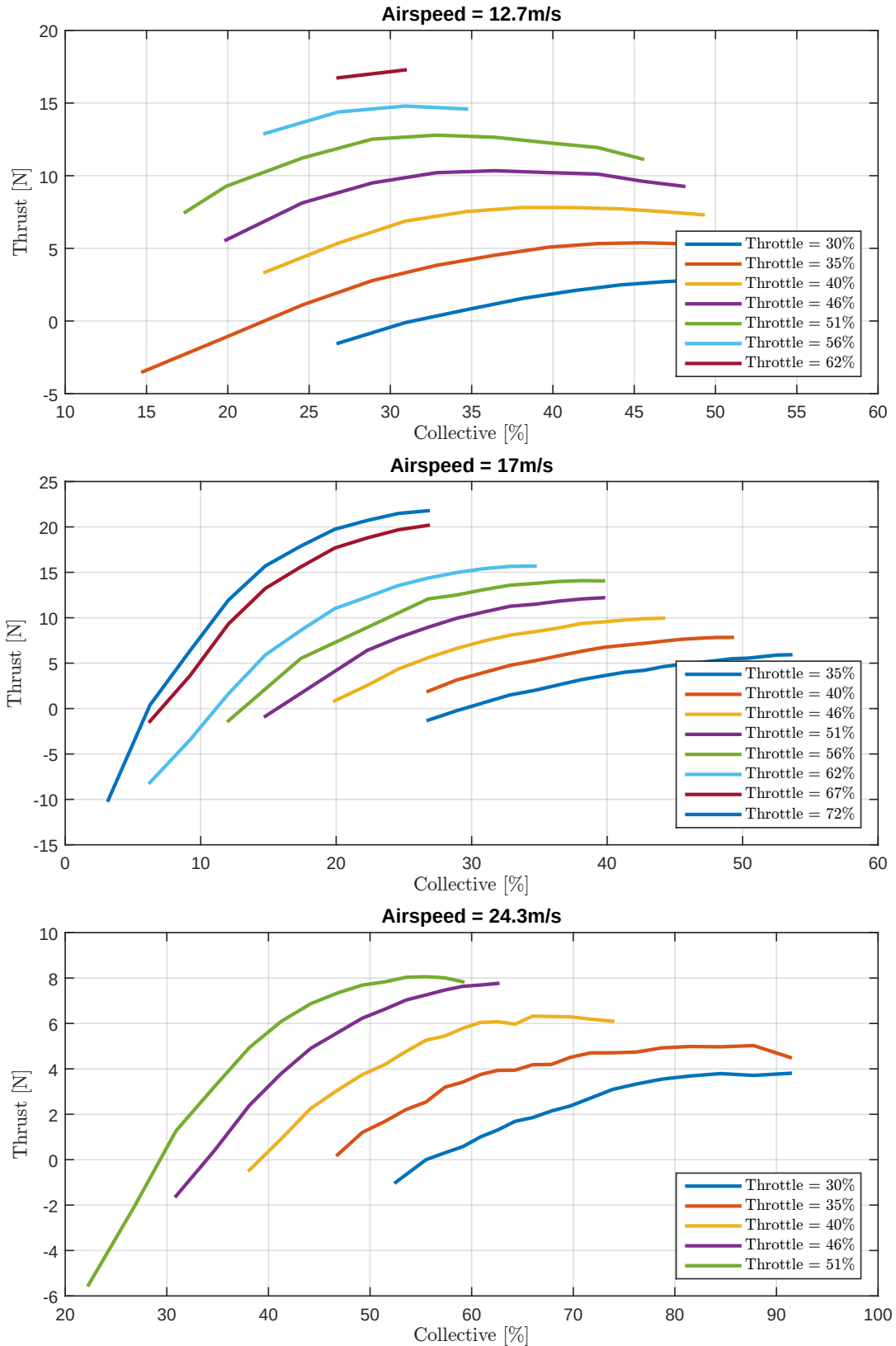


Figure 11: Propulsion power in function of thrust for the 24 inch DelftaCopter rotor.

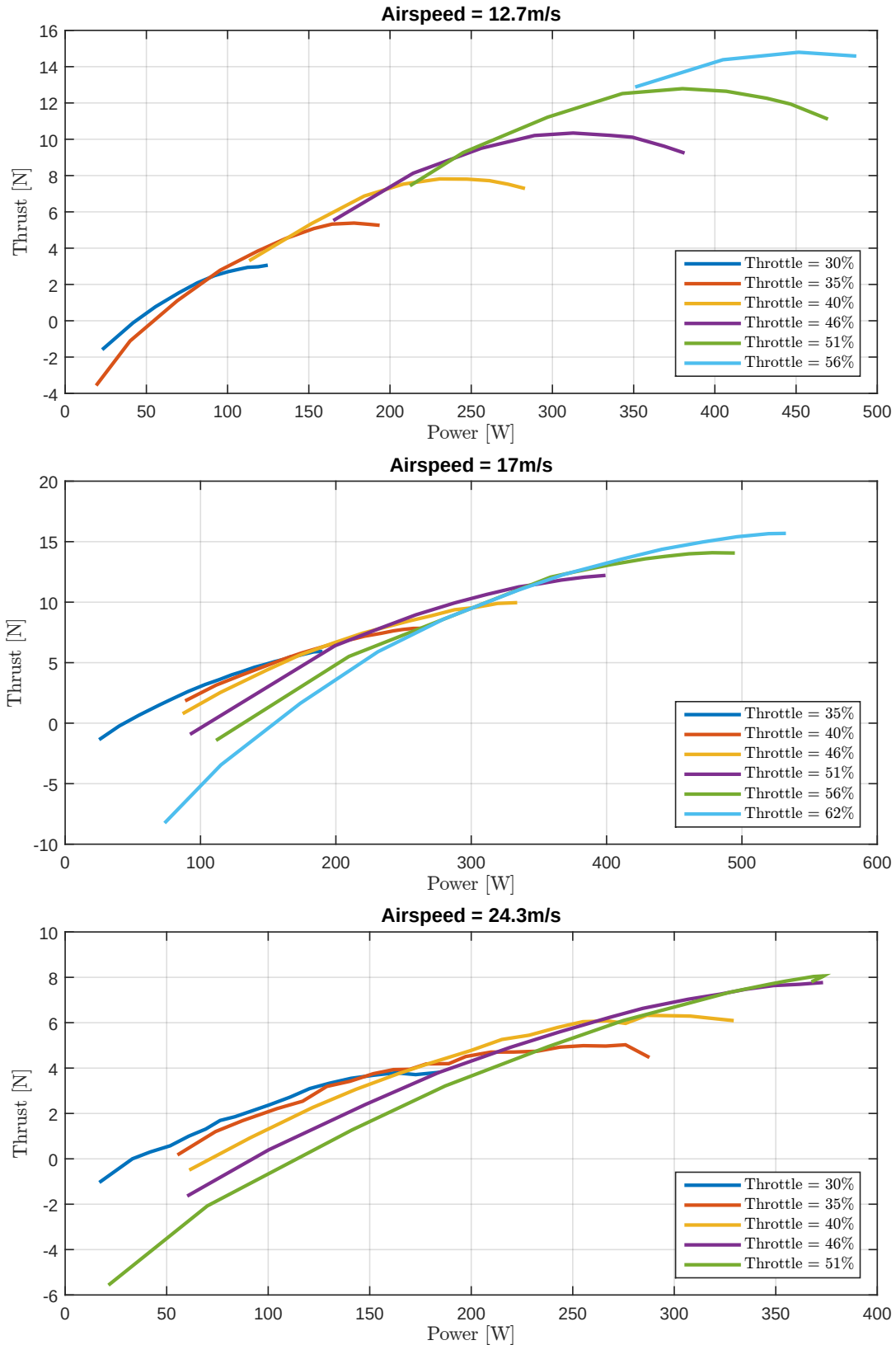


Figure 12: Power in function of Thrust for the 24 inch DelftaCopter rotor.

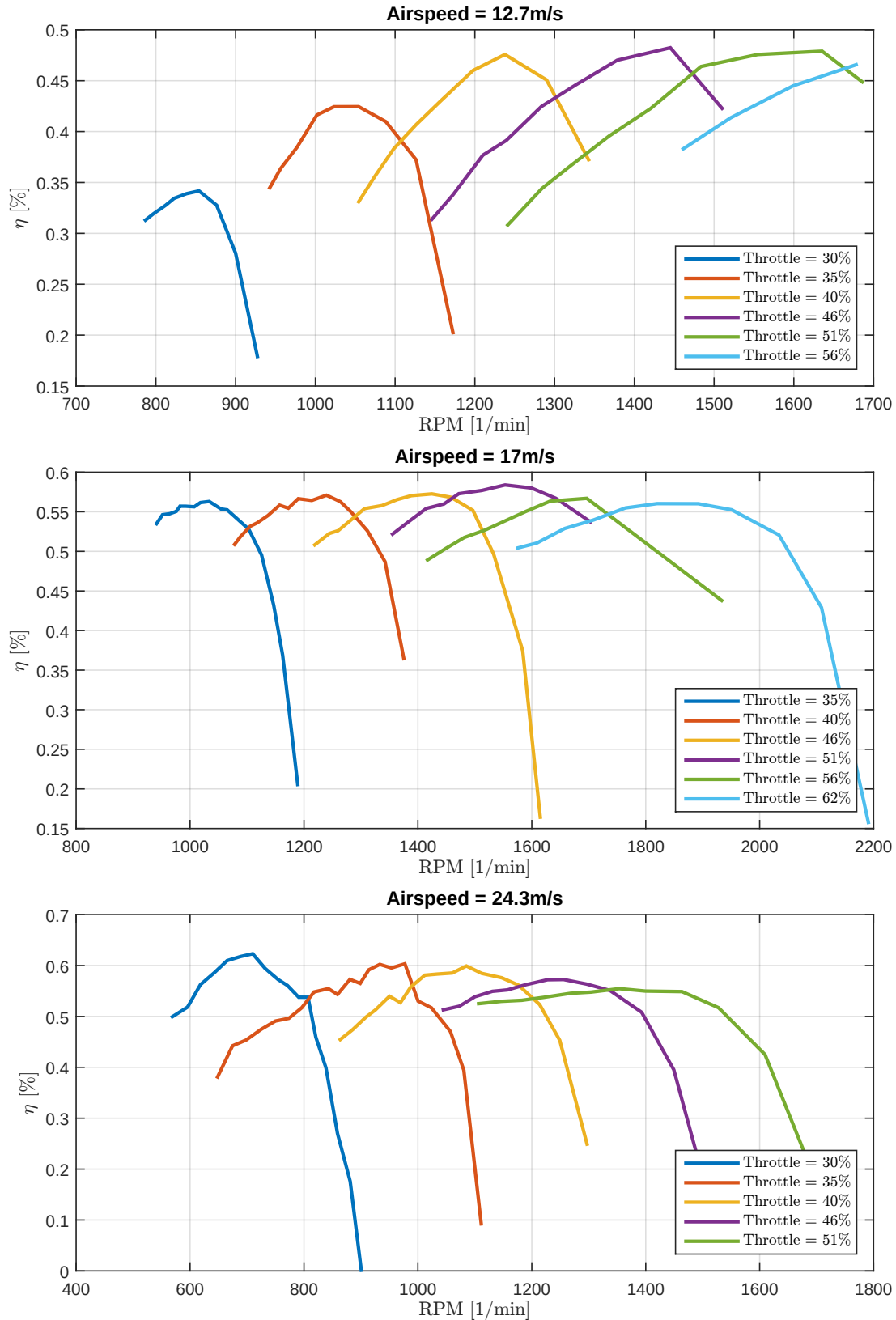


Figure 13: Propulsion efficiency in function of rotor speed for the 24 inch DelftaCopter rotor.