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Experimental study into optimal configuration and operation of two-four rotor coaxial systems for e-VTOL vehicles

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Abstract: Coaxial rotors can be found in multirotor aerial vehicles for the added thrust compared to independent rotors while keeping similar area footprints but, performance losses should be considered. This experimental study analyzes the effects of varying motor throttle and propeller pitch values in motor-propeller systems with two to four coaxial rotors. The results show that in a two-rotor coaxial system, to lessen the adverse effects of a front rotor's backwash and to operate at the maximum performance, only the back motor should be operated initially up to 75% duty cycle before using the front motor up to its 75% duty cycle. Additional thrust requirements should be generated from the back rotor and then from the front rotor up to their maximum duty cycles. In two, three, and four-rotor coaxial setups, total thrust output generated is 1.6, 2.1, and 2.5 times the thrust output at system thrust performance of 86%, 76%, and 66%, respectively of that of an isolated rotor. In a four rotor coaxial setup, maximum system performance is achieved when the propeller pitch values are gradually increased from the first to the last rotor. The gradual increments in propeller pitch values also result in more uniform thrust sharing among rotors.

1. Introduction

1.1. Background

 Multirotor aerial vehicles, like Electric Vertical Take-off and Landing (e-VTOL) vehicles use more than one motor-propeller system to generate the necessary lifting forces. The first multi rotor vehicle built dates back to 1907, but due to the lack of proper control strategies and technologies [1], their development reached a standstill. In the 1990s, advances in Micro-Electro-Mechanical Systems (MEMS), micro processing and Brush-Less Direct Current (BLDC) technologies lead to a wide emergence of electric multi rotor vehicles [2] which are used in various fields today. Multirotor aerial vehicles have created for themselves large markets in photography [3], survey and spatial mapping [4], agriculture [5], surveillance [6], search and rescue [7], fire-fighting [8], pay-load transport [9] and various other purposes [10,11]. Based on the type and scale of application, the size of the multirotor vehicle and parameters like battery type, control strategies, number of rotors as well as its rotor configuration can differ from one vehicle to another.

 Multirotors vehicles primarily use BLDC motors powered by lithium ion or lithium polymer batteries and two or three-bladed propellers. The multiple motor-propeller/rotor systems are usually built in a multi-axial configuration wherein each rotor has its own rotation axis. All the rotors lie in a same plane and do not overlap one another. It is advantageous to use the multi-axial rotor configuration when there are no limits on the size or area footprint of the vehicle. Yet, in many cases, there exist several constraints that limit the vehicle size while requiring it to carry a certain payload [12]. A minimum

payload limit translates to a minimum thrust output requirement by its rotors. A multi-axial configuration can be limiting in such scenarios, as the minimum area footprint almost linearly increases with each additional rotor. In such situations, a coaxial configuration [13] wherein one rotor is placed on top of another, aligned along same rotational axis can be used. This setup allows for substantially increasing its thrust output with no increase in area footprint. Also, coaxial rotor configurations have been utilized in a novel class of multirotor vehicles capable of aerial flight and underwater operation as well as seamless transition in between the two mediums [14]. They have an octo-quad configuration with one set of four rotors on top of another set of four rotors directly under them forming four two-rotor coaxial systems. In such coaxial configurations, fluid interactions occur in between the top and the bottom rotors and cause the system parameters to differ from that of a multi-axial system [15]. In light of these performance deviations, a thorough investigation of the effects is necessary to take advantage and to minimize operational losses in coaxial rotor applications.

1.2. Literature Review

Coaxial rotors have been studied experimentally and analytically since the development of first practical helicopter [16] and the first coaxial design helicopter was patented by Bright [17]. Several research works have evaluated the coaxial rotor performance through experimental, numerical, and theoretical techniques. Balsa wood dust was used to visualize flow and interactions between the top and bottom rotors in a coaxial configuration using a propeller with NASA 0012 airfoil [18] showing that the blade tip vortex patterns remain separate for the two rotors. A survey of research activities performed in several countries into coaxial rotors pertaining to helicopters studied the effect of separation distance, load sharing, wake structure, swirl recovery, etc.[17]. The results indicated that the the back rotor produces lower thrust than usual due to the downwash effect of the front rotor. In regards to the direction of rotation of the two coaxial helicopter rotors, Zimmer [19] calculated a 11% increase in propulsive efficiency for a system of contra-rotating rotors compared to co-rotating rotors.

Leishman and Ananthan [20] used blade element momentum theory (BEMT) to characterize the flow and aerodynamic interactions between two rotors. It is shown that an optimum case for minimum losses occurs when both rotors operate at equal disk loading and equal torques. Xu and Ye [21] used computer models of coaxial helicopter rotors to observe that the bottom rotor is affected more by the top rotor than the inverse.

Lim et al. [22] noted in their experiments with full scale and scaled coaxial helicopter rotors that, with a separation distance greater than just 20% of the rotor diameter, the effect of spacing was minimal. Also, it is shown that the lower rotor only kept 81% thrust while the upper rotor retained 90% of the thrust of a single rotor. While all the papers indicated above made strides in quantifying and/or predicting performance of coaxial rotors in helicopters through experiments, analytical solutions or numerical analysis, they cannot be fully extended to multirotor propellers which more closely resemble the propellers of a model airplane than those of a model helicopters. This difference is as a result of the fact that helicopter blades have a variable pitch controlled through a swashplate mechanism while multirotor blades, as seen in electric quad-rotors, have a fixed pitch.

Brandt and Selig [23] recognized the need for propeller data and tested 79 propellers in a wind tunnel across diameters ranging between 9 and 11 inches and from several manufacturers. Calculated efficiencies varied between 28% and 65%, highlighting the importance of proper propeller selection for multirotor vehicles. Testing performed by Merchant [24] preceded Brandt and Selig's work, but covered 31 propellers made from wood, glass fiber composites or carbon fiber composites and included diameters from 6 to 22 inches.

Two propeller coaxial configurations were tested experimentally by Brazinskas [25] for inter-planar separation between 5% and 85% of the rotor's diameter. A 4% increase in system efficiency for a contra-rotating rotors over the efficiency of a co-rotating rotors

was noticed. The lower rotor's thrust output reduced by 21% at all tested inter planar separations. Also, a reduction in efficiency of about 33% to 42% of lower rotor was observed at different axial separation distances. Buzzatto et al. [26] developed a benchmarking platform for two rotor coaxial system and demonstrated that utilizing the same control input for both rotors results in inefficient thrust performance.

Bondyra et al. [15] concluded that using a octo-quad configuration for a multirotor vehicle can generate about 40% more thrust after discounting the weight of four additional motors. It is also indicated that about 17-29% more power would be required by a 2 rotor coaxial setup to produce same thrust as that of two independent isolated rotors. Propeller pitch values were varied by Simoes [27] and it was concluded that increasing the pitch on the back rotor increased the efficiency of the system and vice versa. Laksminarayan et al. [28] used computational methods to evaluate micro-scale coaxial rotor configurations and observed that when axial spacing increases, thrust from the top rotor increases from 55% to 58% of the total thrust output while that from the bottom rotor reduces.

The existing coaxial rotor studies pertaining to propellers concern themselves with quantifying the thrust and efficiency losses, thrust sharing between propellers and the influence of axial separation distance. A thorough work on coaxial rotor systems as related to multirotor vehicles studying the systemic and individual effects on rotors by varying the motor duty cycle inputs as well as propeller pitch values independently is missing. The effects of adding additional rotors to the two rotor coaxial systems are also not researched and are looked into in this paper along with propeller pitch variation and for the whole range of duty cycles. Thrust output and thrust performance of individual rotors and of the system are calculated from voltage, current and thrust measurements and used to identify superior configurations. These results can be utilized to better design coaxial rotor systems in eVTOL vehicles.

2. Materials and Methods

Two to four-rotor coaxial systems are built in order to determine the effect of varying the motor duty cycles and propeller pitch values on thrust output and performance. Experimental setup utilized, shown in Figure 1 and Figure 2, is used to observe the effects on the individual rotor outputs as well as on the whole system.

2.1. Experimental Test-Bed

The test bed consists of motors, propellers, load cells, support rods, Data Acquisition (DAQ) system , Electronic Speed Controllers (ESC), DC power supply and a tachometer as shown in Figure 1. A motor along with its propeller is mounted on to a load cell suspended at the end of a cylindrical support rod which extends one foot off of a sturdy table to which it is bolted. A power supply provides steady DC power to the motor through a current sensor and an ESC. A servo tester produces a Pulse-Width Modulated (PWM) signal and is used to regulate the duty cycle of the motor through the ESC. Measurements of thrust output and current draw by the motors is recorded using a data acquisition system (DAQ) which includes an Arduino Uno R3. Strain gauge based load cells with HX711 load cell amplifiers, ACS712 current sensors and servo testers used are properly calibrated before each set of experiments and feed data to a PC through the Arduino serial connection. The motor speeds are measured using a hand-held DT-2234C+ digital laser tachometer. A coaxial rotor experimental setup is built by mounting each motor and propeller setup, as shown in Figure 2, on two to four adjacent support rods separated by a distance $d = 4$ inches. This setup enables the testing of multiple coaxial motor-propeller systems separated axially by very small distances.

A BLDC rated for use with a six cell battery and a 13 inch diameter propeller is selected for the tests. Eight of these motors are individually tested and four of them with the most consistent results are used. The maximum thrust deviation among all the motors tested is found to be only 2%. The motors are powered using the DC power supply at 24.0 volts. The motors are matched with 13" propellers as recommended by the manufacturer and
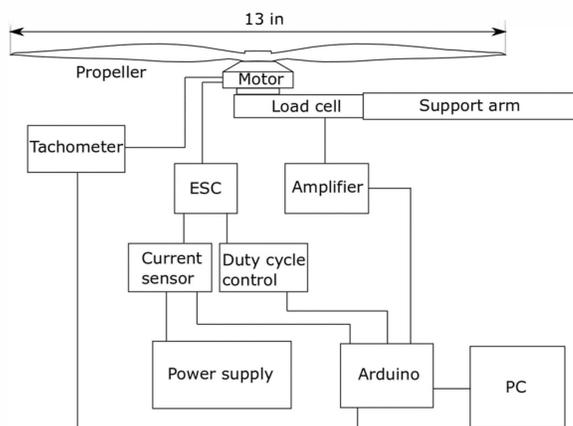
Figure 1. Line diagram showing the different components of the experimental setup.
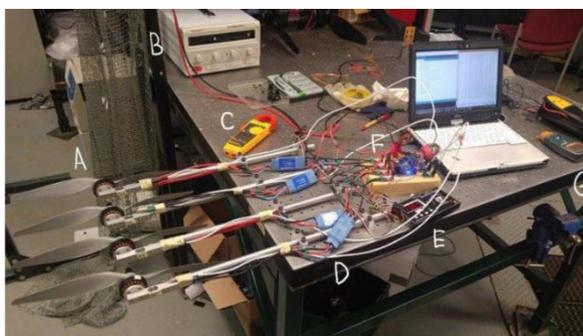
Figure 2. Coaxial rotor experimental setup built at Rutgers University, NJ to conduct tests.

the diameter is kept constant for all experiments. A 4.4" pitch propeller is selected for all experiments unless otherwise specified. The 4.4" pitch propellers are made of carbon fiber and propellers with other pitch values are from "APC" and made from glass fiber composites. The propeller pitch values of the selected APC propellers range from 4 inches to 10 inches and their designs are consistent with an Eppler E63 airfoil blend with a Clark-Y airfoil. All the propellers are properly balanced and their properties are given in Table 1 where factor k is the constant thrust to torque ratio of that propeller.

Table 1. List of propellers tested

Diameter (in)	Pitch (in)	Material	Factor k
13	4.0	Glass fiber	7.758
13	4.4	Carbon fiber	6.180
13	5.5	Glass fiber	6.570
13	6.5	Glass fiber	5.959
13	8.0	Glass fiber	5.605
13	10.0	Glass fiber	4.608

2.2. Accuracy of Measurements

Thrust output, measured in gram-force, and thrust performance, measured as gram-force of thrust output per unit power consumed in watts, are used as metrics [15,26,27]. These metrics are inline with metrics utilized during UAV design [29] and for direct comparison with vehicle weight and payloads [29]. Uncertainties in thrust and thrust performance measurements are calculated based on the maximum thrust and current conditions. The uncertainty is calculated according to the equipment specifications for the load cell and

amplifier, the full scale uncertainty, calibration scale resolution, noise, temperature drift, and offset drift. They compound to a total bias of ±22.5 gram-force in the maximum thrust measurement, constituting to a 2.04% error on the measurement. Uncertainty of the current sensor module is 0.458A and aggregates calibration ammeter accuracy and resolution, sensor noise, and full scale uncertainty. This error calculated for a motor operating at maximum current draw constitutes 4.60% of the measurement. Thrust performance uncertainty is calculated using the differential approach of calculating propagated error on the equation for performance and evaluated using maximum thrust and current values as done above. The uncertainty is 0.232 g/W, which is 4.81% of performance of a motor operating as mentioned.

3. Results and Discussion

Typical thrust output and performance results at different duty cycle values and propeller pitch values of independent rotors as well as complete systems of two to four coaxial rotors are discussed in this section.

3.1. *Two Rotor Coaxial System*

The duty cycles of the front and back motors in a two rotor coaxial system setup are varied together and also independently to compare thrust output and performance of individual rotors to that of the combined system. Propellers of diameter 13 inches, and with a pitch of 4.4 inches are utilized.

### 3.1.1. Duty cycle effects on the individual rotors in a two rotor coaxial setup

The front and back rotors are each independently operated while the other rotor is turned off to measure the thrust generated in gram-force by the individual rotors. Duty cycle is incremented in steps from 0 to 100% while thrust output and current-draw by the motor are measured. The front rotor thrust for the front rotor only operation and vice-versa for the back rotor are indicated in Figure 3 a. It shows that the thrust generated by the front and back rotor, in a coaxial configuration, during independent operation are very similar and match closely with that of an isolated motor-propeller system. When the duty cycle of both rotors is incremented simultaneously, the thrust output from each rotor is indicated in Figure 3 b, to compare to the individual rotor operation seen in Figure 3 a. It shows that the front rotor's thrust output does not change while that of the back rotor is consistently lower at all duty cycles and loses about 36% thrust when compared to independent operation at 100% duty cycle. This agrees with results from the reviewed literature that, for a coaxial setup, the back rotor is affected adversely due to the operation of the front rotor. This is due to the drag force caused on the back rotor due the backwash from the front rotor. Overall, a 21%, 19%, 23% and 19% loss in total system thrust is observed at 25%, 50%, 75% and 100% duty cycles respectively. This is calculated by comparing the sum of the thrusts during combined operation shown in Figure 3 b compared to the sum of the thrusts during the individual rotor operations shown in Figure 3 a. As a result, using a two rotor coaxial system results in about 20% loss in system thrust compared to two isolated rotors.

The results from Figure 3 a and b show that the coaxial rotor configuration causes the back rotor to be adversely affected more than the front rotor. To more closely understand and observe these effects, the front rotor is operated at a fixed duty cycle (0, 25, 50, 75 or 100%), while the back rotor's duty cycle is incremented in steps from 0 to 100% as shown in Figure 4 a . This shows that front rotor's thrust at any fixed duty cycle, remains relatively constant while back rotor's duty cycle is varied. When the same is tested for the back rotor, as shown in Figure 4 b, back rotor's thrust gradually decreases while front rotor's duty cycle is increased from 0 to 100%. The thrust reduction is significant and for example, while the back rotor is operated at 75% duty cycle, a thrust drop of 507 gram-force is experienced by it. When the back rotor is turned off, i.e. at 0% duty cycle, the backwash caused by the rotating front rotor induces a drag force of 180 gram-force on the the back rotor seen as negative thrust in Figure 4 b. The front rotor's backwash also causes the back rotor to have
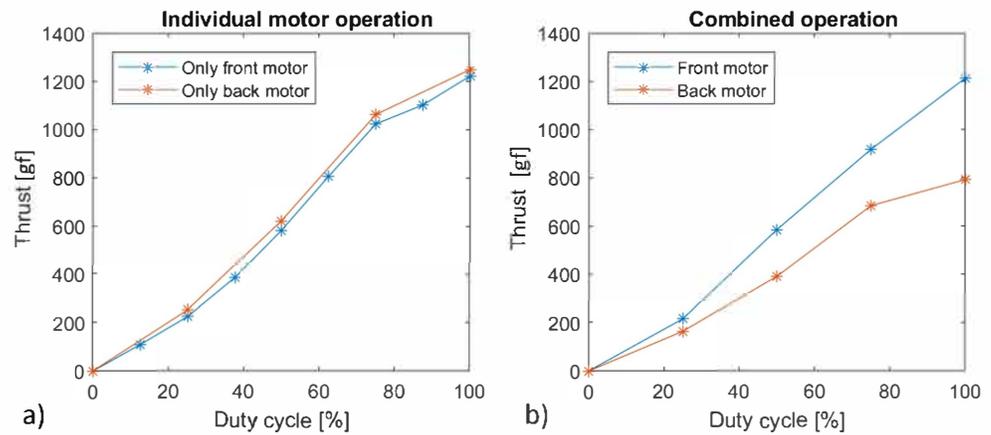
Figure 3. Thrust output from front and back rotors when (a) Front and back rotor are run individually and (b) Both rotors are simultaneously operated.

a non-zero inlet free stream velocity while that of the front rotor is 0 m/s. The two plots   207
corroborate our previous finding that back rotor is affected more adversely than the front   208
rotor in the coaxial setup.
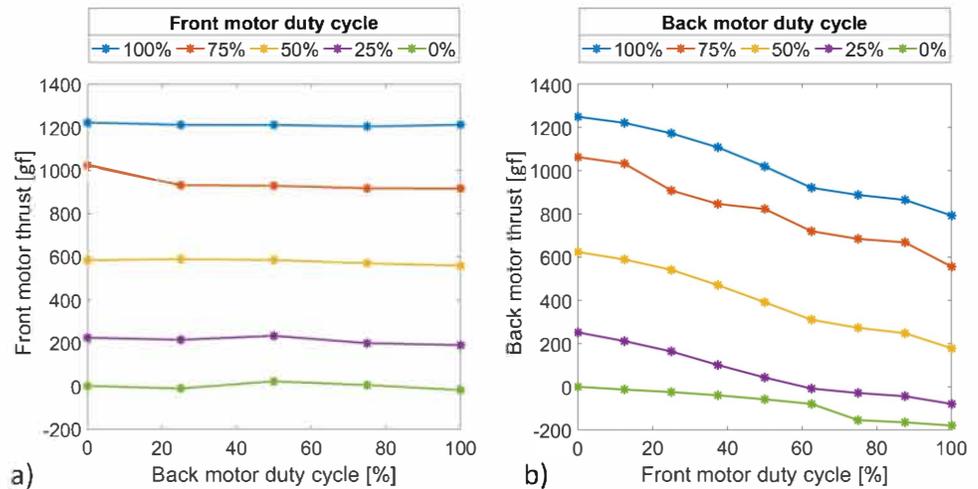
Figure 4. (a) Front rotor thrust output while back motor's duty cycle is incremented. (b) Back rotor thrust output while front motor's duty cycle is incremented.

209

    A key indicator for the effectiveness and efficiency of motor-propeller systems is thrust   210
performance which is defined as the thrust generated by a rotor for each unit of consumed   211
power and measured in gram-force of thrust per watt. Thrust performance is calculated   212
by measuring a propeller's thrust output and its motor's power consumption. The effect   213
of coaxial setup and variation of the back rotor's duty cycle on the front rotor's thrust   214
performance is shown in Figure 5 a. It shows that the front rotor's performance at very   215
low duty cycles (around 25%) reduces by about 17% as back rotor duty cycle is increased   216
from 0 to 100%. And, the front rotor performance at higher duty cycles (25% to 100%) is   217
not affected by the back rotor's operation and remains unchanged. An analogous figure for   218
back rotor shown in Figure 5 b shows that back rotor's performance is significantly affected   219
by front rotor operation. It is observed that, as the back motor duty cycle is lowered, the   220
adverse effect on its thrust performance due to the front rotor increases. At 25% back   221
motor duty cycle and high front rotor duty cycles (>60%), the front rotor's backwash causes   222

the back rotor to have a net negative thrust output and consequently a negative thrust performance value. Overall, higher performance is achieved for a rotor at a lower duty cycle while the other rotor is turned off and this is true also for isolated rotors. Additionally, negative values of thrust and thrust performance are experienced by back rotor at lower back motor duty cycles and high front motor duty cycles which should to be avoided.
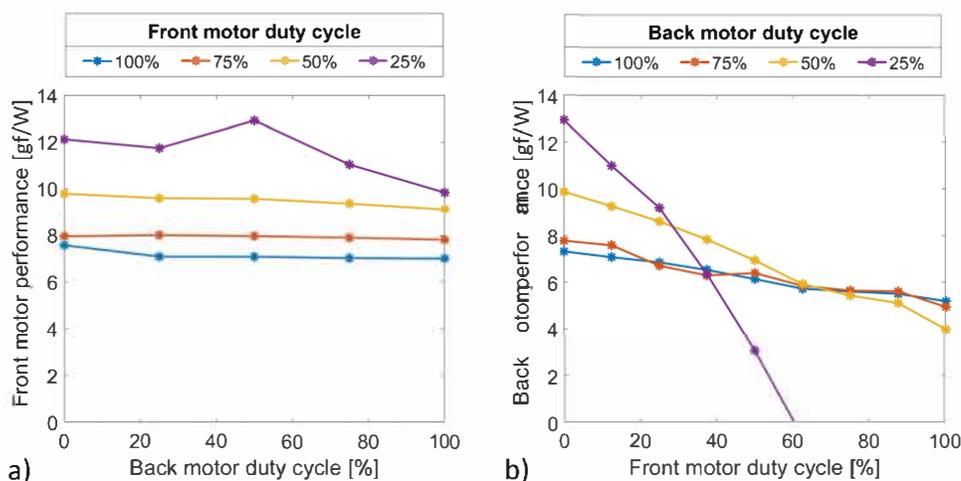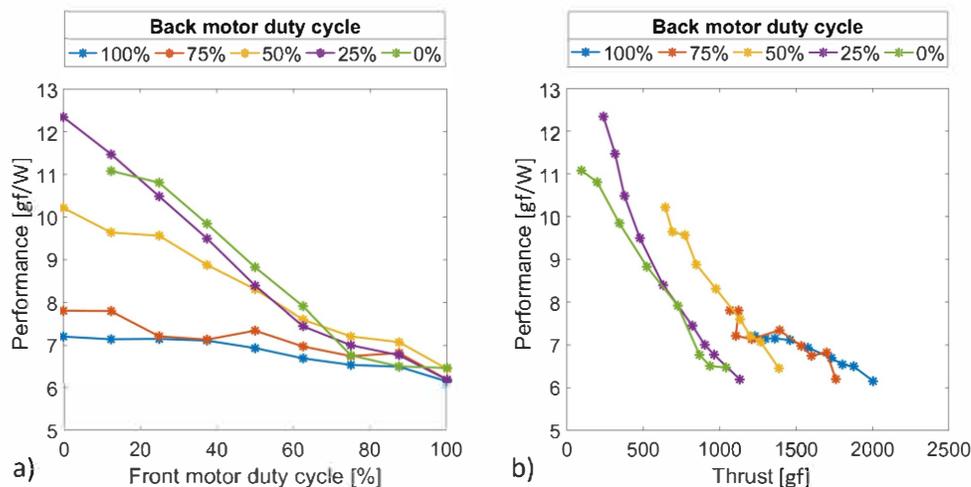

Figure 5. (a) Front rotor performance for different back motor duty cycles. (b) Back rotor performance values for different front motor duty cycles.

3.1.2. Duty cycle effects on the combined system in a two rotor coaxial setup

A system level analysis beyond the individual rotor results is performed to evaluate the net useful effect of two rotor coaxial propulsion system. The thrust outputs from the two rotors and total power consumption are measured to calculate net useful thrust and thrust performance at varying duty cycles. The system performance is plotted for several fixed back motor duty cycles while front rotor duty cycle is incremented as shown in Figure 6 a. The figure indicates that in general, when either front or back motor duty cycle is increased, system performance values drop significantly. When front motor duty cycle is increased, the drop in system performance is higher for lower back motor duty cycles than that for higher back motor duty cycles. System performance reduces to about 6 g/W when the front motor duty cycle is increased to 100% duty cycle irrespective of the back motor duty cycle. System performance values are plotted against the total thrust output for multiple back rotor duty cycles to determine the maximum performance possible for a given thrust requirement and the duty cycle combination capable of achieving such a result. As shown in Figure 6 b, it can be seen that a particular total thrust output can be obtained at several back motor duty cycles. The plot also shows that, for a specific thrust output requirement, a higher system performance is achieved by using a duty cycle combination with a higher back rotor duty cycle and its corresponding front motor duty cycle.

The performance benefit of utilizing the back rotor's thrust first instead of the front rotor is more clearly indicated through Figure 7 a and b. These figures show system performance variation for three cases: when only the front rotor is operated, when only the back rotor is operated, and when both rotors are operated simultaneously at the same duty cycle. Figure 7 a shows that operating only one rotor results in similar thrust-performance values irrespective of the rotor location in a coaxial setup at all duty cycles. Yet, when both rotors are operated together, incrementing their duty cycles simultaneously, the system thrust-performance is significantly lower compared to that of individual rotor operation. From Figure 7 b, it can be seen that the combined operation generates a maximum of about 2000 gram-force of thrust compared to about 1200 gram-force of thrust for the back rotor only operation. Also, it is evident from the figure that the system performance is nearly

Figure 6. System performance values for different back motor duty cycles against (a) Front motor duty cycle and (b) Total thrust output.

10% higher for the back rotor only operation compared to the front rotor only operation at most system thrust outputs. Also, the maximum system thrust output is 18% higher for the back rotor operation than that generated by the front rotor. The lower system thrust and performance observed during front rotor only operation is due to the negative thrust induced by the front rotor's backwash on the back rotor even when the back motor is turned off.

As a system, the back rotor generates thrust at a superior thrust performance than the front rotor when the other rotor is turned off. Hence when the thrust requirement is low, back rotor only operation should be preferred for a lower power consumption. From Figure 7 b, it may also be concluded that, for much higher system thrust requirements (1000 to 1200 gram-force), instead of operating only the back rotor at very high duty cycles, a higher thrust performance can be achieved by operating both rotors together at a corresponding duty cycle which is lower. This is because, thrust performance of a motor-propeller system is higher at lower duty cycles as shown in Figure 7 a. And, the performance benefit of having both rotors operate at a lower duty cycle is higher than the negative effect of the backwash drag on the back rotor due to the front rotor.

Front and back motor duty cycles are varied independently to determine the best duty cycle combination to achieve a required system thrust output with the maximum possible system thrust performance. System thrust and performance heat maps are generated and shown in Figure 8. Figure 8 a indicates that when the duty cycles on either motor is increased from 0% located at the left or bottom edge of the map to 100% located at the top or right edge of the map, system thrust output increases monotonously. And, Figure 8 b shows that the higher performance is achieved at lower duty cycles where unfortunately lower thrust is generated and, for higher thrust outputs, higher duty cycles are required where poor system performance is observed. In view of this negative correlation between thrust and performance, a duty cycle path needs to be chosen to increase thrust output from the 0% duty cycle (zero thrust) corner to the 100% duty cycle (maximum thrust) corner. This path increments either front or back motor duty cycle individually, to increase thrust output such that the least possible performance is compromised as a result in each step. Using the system thrust and system performance maps shown in Figure 8 a and b, the optimal path includes first increasing back motor duty cycle to almost 75% and then incrementing front motor duty cycle from 0% to about 75%. If additional thrust is required, back motor duty cycle is to be maximized to 100% before increasing the front motor duty cycle to 100%. This path results in retaining the maximum possible system performance for any required total thrust output.
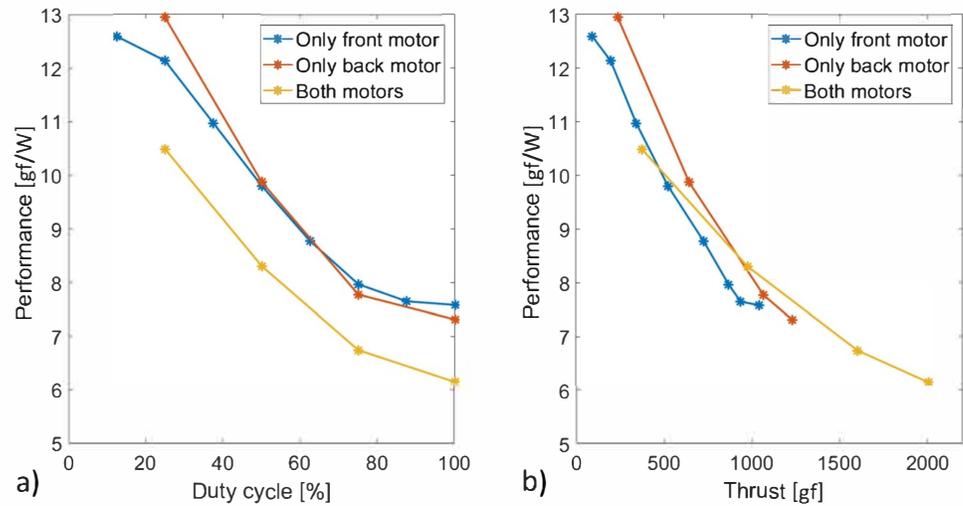
Figure 7. System performance for individual rotor runs compared to combined operation against (a) Duty cycle and (b) Total thrust output.
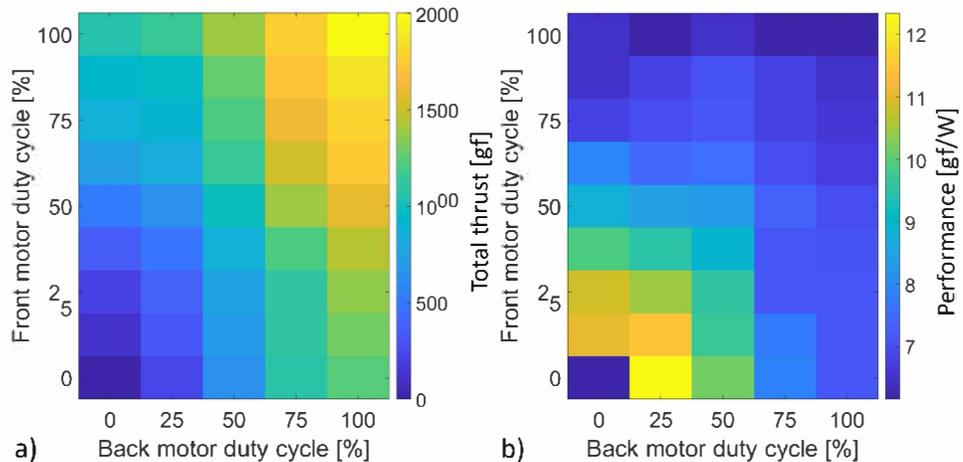
Figure 8. (a) System thrust output heat map and (b) System performance heat map for incremental front and back motor duty cycles.

3.2. Additional Coaxial Rotors

The effect of adding a third and a fourth rotor to the two rotor coaxial system on system thrust output, performance and thrust sharing among rotors is analyzed in this section. The effects of pitch variations in a four-rotor coaxial system are also investigated.

3.2.1. Thrust and Performance Variations

The increase in the total thrust of a coaxial system with each additional rotor in comparison to a multi-axial system (up to four rotors) is indicated in Figure 9 a. Each motor is supplied equal power input and the the total thrust output of the four rotors is plotted in the figure. The total thrust output with 2,3 and 4 rotors is 1.6, 2.1 and 2.5 times that of a single rotor respectively. The system performance for the same is plotted in Figure 9 b and shows a gradual reduction of thrust performance in comparison to an isolated rotor with values of 85.5%, 75.5% and 66.4% for 2, 3 and 4 coaxial rotor systems respectively. It can be seen from these two plots that each additional coaxial rotor increases the total thrust by a fraction of the thrust of the rotor immediately in front of it. And this increment in thrust is accompanied by a decrease in the system performance.
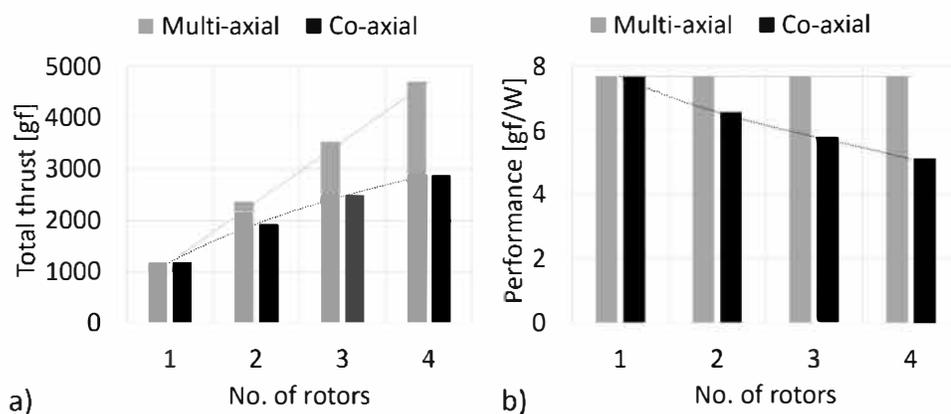
Figure 9. (a) Total thrust output and (b) System performance for one to four rotor coaxial systems compared to multi-axial systems.

Thrust sharing among the rotors in the 2-4 rotor coaxial systems is shown in Figure 10 to determine the thrust loading and the fraction of total thrust produced by each rotor. It shows that first rotor's thrust is greater than second rotor's thrust which is greater than third rotor's thrust which is greater than fourth rotor's thrust for the four rotor coaxial system. This relation holds true even for 2 and 3 rotor coaxial systems. For the coaxial setup with four rotors, the thrust output of each rotor from the first rotor to the fourth rotor is 91%, 68%, 49% and 37% of that of an isolated rotor respectively. This indicates that a coaxial system with the same pitch value on all propellers results in a uneven thrust sharing between motors with the largest portion of total thrust being generated by the frontmost rotor and the smallest fraction produced by the rearmost rotor.
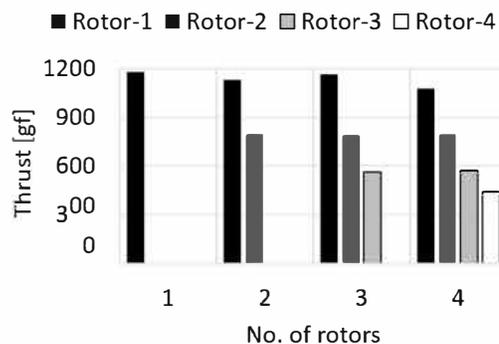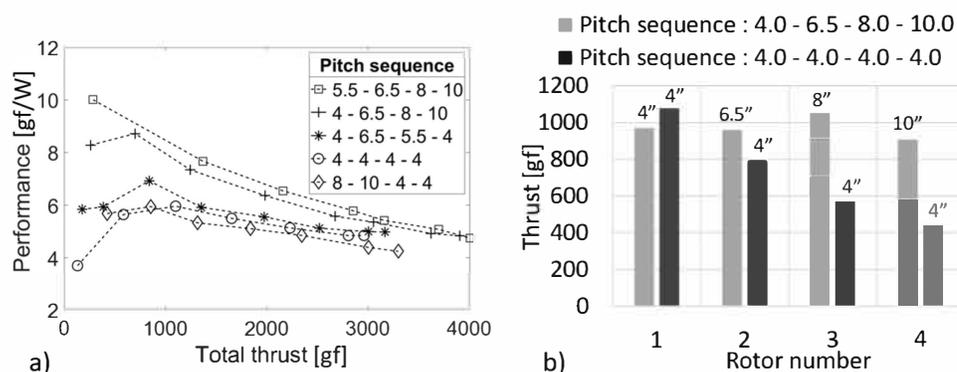

Figure 10. Thrust distribution among rotors for one to four rotor coaxial systems.

3.2.2. Pitch variation in a Four-Rotor Coaxial System

Several propeller pitch combinations are tested on the four rotor coaxial setup to observe the effects on system thrust and performance and to determine the best pitch combination. Out of the five pitch combinations tested, highest performance is observed when the propeller pitch values are incremented from the first rotor to the last rotor. Also, the lowest performance is observed when the propeller pitch values are decremented from the first to the last rotor. Results are shown in Figure 11 a where system performance for five different pitch combinations is plotted against total thrust output while the duty cycle signal on all four motors is simultaneously increased from 12.5% to 100%. The lowest system performance at almost all duty cycles is observed for the propeller pitch combination of 8", 10", 4" and 4" from the first propeller to the fourth propeller. In this pitch combination,

the first two propellers have very large pitch values of 8" and 10" while compared to 4" 328
pitch on the third and fourth propellers. The top two best system performances at all duty 329
cycles is observed for the pitch combinations of 5.5", 6.5", 8" and 10" and 4", 6.5", 8" and 330
10". Both pitch combinations follow the same pattern wherein the propeller pitch values 331
increment gradually from the first propeller to the fourth propeller. The 5.5", 6.5", 8" and 332
10" pitch combination has a slightly higher maximum total thrust at 100% duty cycle than 333
the 4", 6.5", 8" and 10" pitch combination. And, it also has a slightly higher performance 334
since its front most 5" pitch propeller can generate same thrust as the 4" pitch propeller at 335
a lower duty cycle corresponding to a higher performance value. Figure 11 b shows the 336
distribution of the total system thrust among the four rotors in the coaxial setup for two 337
cases. The coaxial system with all 4" pitch propellers is compared to a system with 4", 6.5", 338
8" and 10" propeller pitch combination. For the latter pitch combination with sequentially 339
increasing pitch values, the second, third and fourth rotors generated about 99%, 108% and 340
93% respectively compared to that of the first rotor. The tests indicate that, similar to the 341
two rotor coaxial systems [27], better performance is achieved when propeller pitch values 342
increase incrementally from the first to the last propeller. This also helps to achieve uniform 343
thrust distribution among all the rotors in a coaxial system.

Figure 11. (a) System performance of four rotor coaxial system for different pitch combinations. (b) Thrust distribution among rotors for sequentially increasing and constant pitch combinations.

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4. Conclusions
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Experimental analysis of coaxial rotors with two to four-rotors is conducted to deter- 346
mine optimal configurations and system strategies for improved operation. Specifically, 347
motor duty cycle (throttle %) and propeller pitch were evaluated to compare different con- 348
figurations and operational strategies. Experiments are conducted using 13 inch diameter 349
propellers of different pitch values. Thrust output and thrust performance measured in 350
gram-force per watt of individual rotors and complete systems are used to compare the 351
results from different experiments. Experiments corroborated previous published works on 352
coaxial rotors where the back rotor performance is adversely affected by the front rotor's 353
backwash. They also showed that adopting a coaxial two-rotor configuration instead of a 354
two-rotor multi-axis system reduces the system thrust output by only 20% while cutting 355
down its area footprint by 50%. 356

In order to operate a two-rotor coaxial system always at maximum thrust performance, 357
only the back motor should be utilized initially up to 75% duty cycle before increasing the 358
front motor's duty cycle up to 75%. Additional thrust requirement should be met by the 359
back motor and then by the front motor up to their maximum duty cycles. Coaxial rotor 360
systems with two, three and four-rotors generated 1.6, 2.1 and 2.5 times the thrust output 361
at system performance of 86%, 76% and 66% respectively of that of an isolated rotor. Also, 362
thrust sharing among rotors is not uniform and decreases for all downstream propellers 363
for the same power input to all motors. Almost uniform thrust sharing among rotors in a 364

four-rotor coaxial system can be achieved by gradually increasing propeller pitch values from the first to the last rotor. For the tested propellers, this was achieved with a pitch combination of 4", 6.5", 8" and 10" for the first, second, third and fourth rotors respectively. Also, the system performance of a four-rotor coaxial system is maximum when propeller pitch values are incremented gradually from the first propeller to the last in contrast to pitch combinations where pitch values are decreased. Utilizing these results to design and operate e-VTOL vehicles is expected to reduce power utilization and extend vehicle range.

Abbreviations

The following abbreviations are used in this manuscript:

BLDC	Brush-Less Direct Current
DC	Direct Current
e-VTOL	Electric Vertical Take-Off and Landing
UAV	Unmanned Aerial Vehicle
PWM	Pulse Width Modulation
DAQ	Data Acquisition

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