THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF AEROSPACE ENGINEERING

EVALUATING AERODYNAMIC PERFORMANCE OF COAXIAL ROTOR SEPARATION DISTANCE

ADEN SCOTT FUNKHOUSER
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Reviewed by the following:

Jose Palacios
Associate Professor of Aerospace Engineering
Thesis Supervisor

Namiko Yamamoto
Associate Professor of Aerospace Engineering
Honors Adviser

Abstract

In recent years, the need for rotorcraft capable of producing large thrust levels while maintaining a relatively small area footprint has revitalized research on the coaxial rotor system. Coaxial rotors offer potential benefits in thrust generation accompanied by a torque cancelation in the overall system that would remove the need for a torque-stabilizing tail system.

The research performed for this thesis focused on experimentally evaluating the aerodynamic performance of a coaxial rotor system with respect to the blade separation distance. Rigid rotor blades were spun at various RPMs to determine if the separation distance has any effect on the thrust and torque generated by the overall coaxial system and each individual blade.

The torque generation by the rotors demonstrated an adverse relationship of small magnitude, with the fluctuation varying non-linearly over the tested separation distances. However, the torque of the overall coaxial system did cancel out to negligible levels at all tested RPMs. Analysis of the acquired data suggested that while there was a relation between the aerodynamic interference experienced by the rotors and their respective aerodynamic performance, blade separation distance did not linearly affect the performance as originally expected. At certain blade separation distances, which varied with RPM, the adverse relationship between the upper and lower rotors of the coaxial rotor system did allow the upper motor to outperform its isolated, single-rotor system results by margins ranging from 3.28 percent to 10.26 percent. These elevated regions dissipated as the RPM increased and disappeared entirely at an RPM of 3000. Therefore, a coaxial rotor system's ability to increase overall system performance by elevating the thrust production of the upper rotor above its respective isolated performance is dependent on blade separation distance and operation RPM.

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Acknowledgments

I want to thank Dr. Sihong Yan for being a constant resource throughout this project. Particularly, I would like to thank Dr. Yan for his work designing and setting up the experimental environment. His work in wiring the electronic components, writing a LabVIEW program to control the tests, and linking the physical and computation interfaces made my research project possible. His initial work allowed me to join the project near the testing phase and focus on understanding the aerodynamic aspects of the experiment. Furthermore, once testing, Dr. Yan was an invaluable resource as I worked to become more technical in the field of rotorcraft aerodynamics.

I would also like to thank my advisor, Dr. Jose Palacios, for guiding me through the learning stages of research. Dr. Palacios was always available to assist with any technical questions throughout the process. In addition, Dr. Palacios' guidance in selecting a topic and scope for my first engineering thesis was extremely helpful and allowed my eventual success with the project.

Chapter 1. Introduction

1.1 History of Coaxial Rotor Systems

Despite most modern helicopters utilizing a single-rotor system, coaxial rotor systems have been around for centuries. The first coaxial rotor concept was developed by Mikhail Lomonosov around 1754. However, while it could generate thrust, it failed to fly due to its heavy weight [5].

The first patent for a "helicopter" design was a coaxial rotor concept and was awarded to Henry Bright by the British Patent Office in 1859 [4]. As the single-rotor concept continued to advance and establish itself, the coaxial rotor system experienced minor progressions.

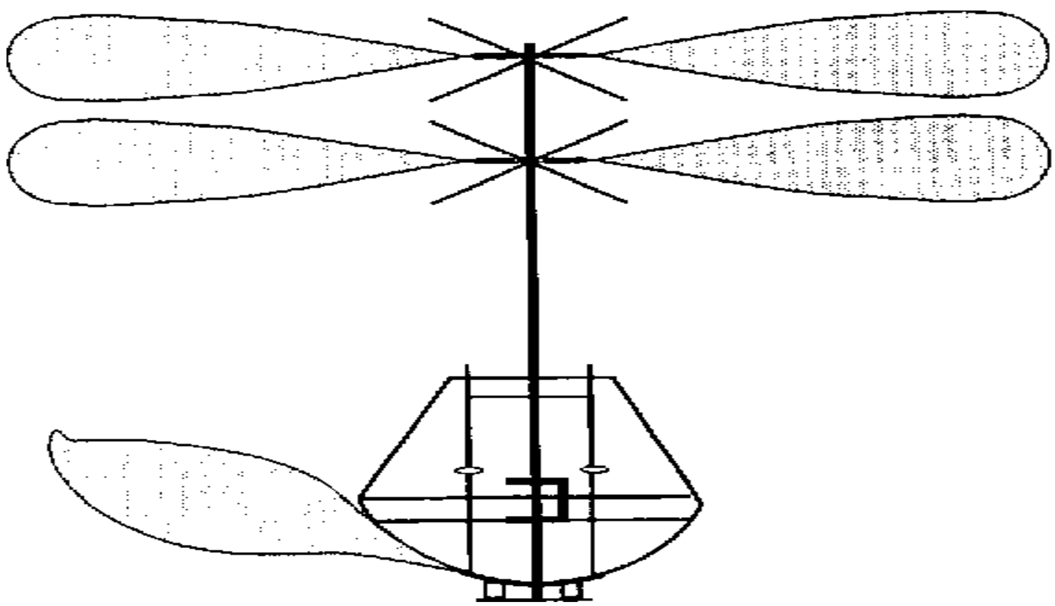

Figure 1. Henry Bright's Coaxial Rotor Concept

However, in the 1950s, the Kamov Design Bureau shifted its focus to the coaxial rotor concept and began to push for the design and production of helicopters with coaxial rotor systems. The Kamov company's Ka-10 helicopter gave purpose to the use of coaxial rotors, as the design proved to excel at taking off and landing on the decks of small ships. Additionally, the production of the Ka-50, a single-seat attack helicopter with coaxial rotors, further validated that the use of coaxial rotor systems was warranted [6].

Figure 2. Kamov Ka-50 Attack Helicopter

Around the same time, the United States started experimenting with the coaxial rotor design, as a full-scale hover test was performed in a wind tunnel at the NASA Langley Research Center [1].

In 1967, the American helicopter company, Sikorsky, experimented with its first coaxial rotor concept via the Sikorsky AARV [8]. The purpose of the rigid counter-rotating rotors was to allow for rotor lift while the helicopter operated at high speeds, but it never advanced past the conceptual design phase [9]. Sikorsky continued experimenting with coaxial rotors via the Advancing Blade Concept (ABC), which was intended to outperform the convention helicopter in two key areas: maximum speed and lift potential. The XH-59A ABC demonstrator aircraft underwent around five years of ground and flight tests and was shown to generate rotor lift while reaching airspeeds of up to 230 knots in level flight but was never put into production [12]. More recently, Sikorsky has designed two revamped versions of the XH-59AX2 ABC demonstrator. The Sikorsky X2 and Raider X feature rigid counter-rotating blades with varying blade twist distributions and vibration reduction technology. Both helicopters operate with a single pilot and engine and have recorded flight speeds of up to 250 knots. Sikorski's current coaxial rotor project, the Defiant X, is an advanced utility helicopter intended to replace the Black Hawk. The Defiant X is expected to be the fastest and most maneuverable military helicopter in history [14].

Figure 3. Sikorsky Defiant X Helicopter

1.2 Research Motivation

In the modern era, the quest for high-speed rotorcraft capable of producing rotor lift has renewed interest in coaxial rotor systems. Coupled alongside this search is the need for rotorcraft with a small area footprint, allowing them to operate in environments with limited space. The smaller area footprint also creates a more maneuverable rotorcraft, which is advantageous for commercial and military use.

Sikorsky's X2 demonstrator has revived interest in the use of coaxial rotor systems on military helicopters. In addition, this success has resulted in many outside organizations performing their own versions of coaxial rotor testing for hover and forward flight. The University of Texas has developed a coaxial rotor test system that has recently been used to validate both computational analysis and CFD methods for predicting the aerodynamic performance of coaxial rotor systems [3].

This thesis will focus on the coaxial rotor system's performance in hover, which is still directly applicable to the X2's overall performance. One of the primary advantages of using counter-rotating coaxial rotors is eliminating the need for an anti-torque tail rotor, as the counter-rotation of the upper and lower rotors balances the torque felt by the rotorcraft. Furthermore, the power left over from eliminating the tail rotor can ideally be used to increase lift generation, which is a critical factor in any military VTOL rotorcraft's ability to land on the decks of ships safely and efficiently [13].

Electrical Vertical Take-off and Landing (eVTOL) vehicles are rapidly becoming more popular in the modern era of aerospace vehicles. EVTOL systems primarily employ a multirotor and multiaxial design, with each rotor lying on its own individual axis. However, this concept can struggle to operate efficiently in small spaces due to issues balancing the rotorcraft's area footprint and payload weight, as an increase in payload weight results in the need for additional rotors [11]. Moreover, as rotors are added to the overall system, the rotorcraft's area footprint proportionally increases, making its use in tight environments more difficult.

Using coaxial rotor systems on eVTOL rotorcraft could potentially solve the issue of balancing payload weight and the craft's area footprint. With a coaxial rotor system, rotors lie on top of each other in the same axis plane, preventing an increase in the area footprint of the rotorcraft as additional rotors are added to the system. Therefore, coaxial rotor systems should generate thrust levels similar to that of a multirotor system using the same number of rotors. A coaxial rotor system's comparable thrust generation and smaller area footprint would result in more efficient eVTOL rotorcraft.

The alignment of counter-rotating coaxial rotors on one axis should allow the thrust generation to be a combination of both rotors in the system. The shared thrust generation should reduce the size of the rotor radius required compared to that of a single rotor system. This is especially relevant to the experiments documented by this thesis, as the tested separation distances are a far larger percentage of the rotor blade radius than that of previous work documented in literature. The current testing setup will allow separation distances of up to 75% of that of the rotor blade radius. This data should offer better insight into the precise effects of large rotor separation distances on the aerodynamic performance of coaxial rotor blades for commercial and military use.

1.3 Review of Prior Research

In recent years, numerous universities and research groups have tested the aerodynamic performance of both counter-rotating and co-rotating coaxial rotor systems. Performance parameters have been recorded for both hover and forward flight; however, the data does not align perfectly between the different studies.

According to Coleman's 1997 findings, altering the separation distance of the blades in a coaxial rotor system in torque-balanced hover while keeping the total thrust generation at a fixed level will only alter what percentage of the overall thrust is generated by the lower and upper rotors. Coleman, therefore, claimed that merely varying separation distance has little practical use, but the elimination of a tail rotor and the additional available power made coaxial rotor systems logical for hovering scenarios [4].

In 2015, research scientist Manikandan Ramasamy used facilities at NASA Ames Research Center to evaluate aerodynamic performance and interference of coaxial rotor systems in hover. The set-up was comprised of a testing stand capable of varying rotor separation distance, blade type (uniform or twisted), and power supply levels. Instead of each rotor having a single blade, each rotor was equipped with three blades. Ramasamy measured the thrust and torque of the upper and lower rotors for axial separations distances ranging between 5% and 150% of the rotor blade diameter. Ramasamy characterized aerodynamic performance via "Figure of Merit," which is a measure of the minimum possible power required to hover divided by the actual power required to hover. Ramasamy identified three main regions of performance results following the testing. When axial separation was less than 20% of the untwisted blade diameter, the upper rotor demonstrated rapidly reducing performance. In contrast, the lower rotor demonstrated improving performance, resulting in an overall decrease in Figure of Merit. When axial separation was between 20% and 75% of the untwisted blade diameter, the upper rotor demonstrated a gradual reduction in performance. In contrast, the lower rotor demonstrated a gradual increase in performance, resulting in the overall Figure of Merit for the system experiencing negligible change. Finally, when axial separation was greater than 75% of the untwisted blade diameter, the aerodynamic performance of the overall coaxial system and each individual rotor was unaffected by changes to the blade separation distance. These results led Ramasamy to conclude that when the axial separation distance decreases, the influence of the lower rotor on the upper rotor increases. Therefore, smaller separation distances resulted in decreased thrust generation and increased torque on the upper rotor. Twisted blades demonstrated similar results for the first region of performance. However, once the blade separation distance reached greater than 20% of the blade diameter, the aerodynamic performance was independent to the blade separation distance [2].

Research performed at Embry Riddle University in 2017 determined that coaxial rotors require an average of 37% more power than an isolated rotor system to generate equivalent thrust levels while in hover, and the power requirement increases as the separation of the blades decreases. For example, Rotor spacing at 10% of the blade radius required 24% more power to reach all tested thrust levels than the baseline rotor, while the power required at 30% of the blade radius was 12% less than that of the baseline rotor. This relation between blade separation and power requirement in hover was attributed to aerodynamic interference between the upper and lower rotors. As the advance ratio increased, the aerodynamic inference between the rotors seemed to decrease at all separation distances [5].

1.4 Research Objectives

The objective of this experimental research was to determine how large percentage separation distances affect the aerodynamic performance of rigid coaxial rotor blades in hover. Separation distance was the independent variable for all tests performed. Specifically, the individual objects of the work were:

1. To investigate how thrust and torque generation relates to the separation distance of rigid rotor blades in a coaxial rotor system in hover

2. To evaluate how the aerodynamic interference experienced by rotors in a coaxial system affects the aerodynamic performance of each rotor by comparing thrust generation values to those recorded when each rotor acted as an isolated, single-rotor system

1.5 Outline of Thesis

1.5.1 Chapter 2: Methodology

Chapter 2 explains the methodology used to perform the tests and process the data. This included detailed information about the setup of the testing environment, calculations for verification of the steady-state RPM, application of a Fast-Fourier Transform for noise analysis, and the process of selecting and applying a post-processing filter to clean up the signal.

1.5.2 Chapter 3: Results and Discussion

In Chapter 3, the results of the performed testing were discussed in detail, including numerous visual aids to demonstrate patterns in the data. This discussion focused on the relationship of a coaxial rotor system's blade separation distance to aerodynamic performance and aerodynamic interference. The discussion also compared each individual motor's performance within the coaxial system to its respective results when ran as an isolated, single-rotor system.

1.5.3 Chapter 4: Conclusions and Remarks

In Chapter 4, final conclusions were drawn about the relationships discussed in Chapter 3. These conclusions were reached after an analysis of each individual rotor system's performance, along with an analysis of the overall performance of the coaxial rotor system. Then, said conclusions were used to detail areas where future work could provide a better understanding of the aerodynamic relationships discussed in this thesis.

Chapter 2. Methodology

2.1 Description of Testing Environment

The testing environment used to acquire the data detailed in this thesis resides in the basement of the Hammond Building at Pennsylvania State University. The layout consists of six DC power supplies, two rotary encoders, two optical lasers, two loadcells, two KDE Direct 8218XF-120 motors, two 27” ABS twisted blades, two thermistors, electrical connection devices, a DAQ device, a computer system equipped with LabVIEW, and an aluminum sliding beam structure.

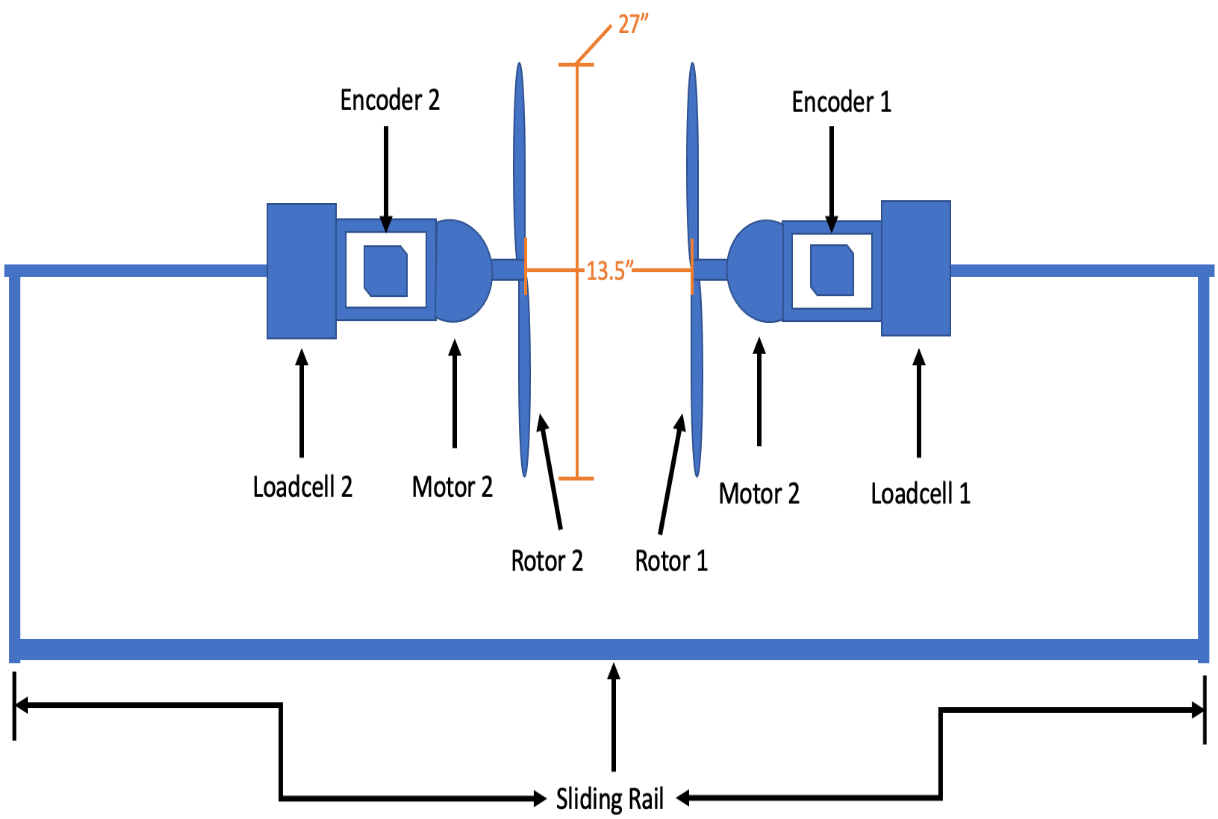

Figure 4. Schematic of Testing Environment

Two of the power supplies are capable of larger voltage output, with each of those feeding directly into the corresponding motor, thermistor, and loadcell. One of the smaller power supplies is connected to the two lasers, with the remaining two small supplies powering the corresponding rotary encoder. The sixth DC supply serves solely as a safety switch, preventing the larger power supplies from being active unless the sixth is turned on. This prevents the motors from receiving the power needed to operate and allows the user to safely enter the room between tests by powering down the sixth supply.

Optical lasers are used as a secondary method to determine the RPM of the motors. Each laser is pointed at a piece of reflective tape placed on the side of its corresponding motor, allowing the system to record the number of times the reflection occurs per minute.

The rotary encoders offer a more precise method of determining the RPM of each motor. Each motor has a maximum operational RPM of 3500 within the testing environment. The encoder records the revolution data of its corresponding motor, which is stored by the DAQ and denoted by either a “0” or “1” in a dataset. This dataset can later be manipulated to determine the RPM of the motor.

Each loadcell records the forces and moments the motor attached to it generates. The data is recorded in the X, Y, and Z planes, but only the Z plane was considered for the results of this thesis. The Z plane force represents the thrust generated by the rotor blade system, and the Z plane moment represents the torque generated by the rotor system. Before testing, the load and torque readings of three distinct directions were verified with a twenty-five-pound weight. Verifying that the loadcell recorded the correct readings in three directions ensures that the load matrix generated by the cell will be accurate and precise. The loadcells are also “biased” and zeroed out on LabVIEW prior to each testing run to avoid inaccurate data. A thermistor also monitors each loadcell's temperature to ensure that overheating does not cause damage or provide faulty readings.

The loadcell and motor systems are mounted on an aluminum beam structure and oriented to lie on the same horizontal axis. The structure features two "L" beams connected by a bottom sliding rail. Once the lowered bolts are loosened, the sliding rail can be retracted/extended, allowing for the testing of different blade separation distances. The beam structure is secured by a mixture of ratchet straps and metal C-Clamps tightened to the point that the entire beam structure is completely rigid. The rigidness of the structure prevents the loadcells from picking up inaccurate torque and force readings caused by extra vibration and movement of the structure. In addition, the aluminum structure is grounded to both total ground and each individual power supply to prevent additional high-frequency noise.

The data recorded by the load cells and rotary encoders are transferred via wireless internet to a data acquisition device (DAQ), which is connected to the computer system. The DAQ device saves the raw data and feeds it to LabVIEW, allowing the user to monitor the results in real time. The loads, temperatures, and RPMs displayed on LabVIEW are fast-changing and unfiltered but are useful in ensuring that no significant issues damage the data. The data recorded by the DAQ is later filtered during post-processing.

2.2 RPM Calculation

As previously mentioned, the rotary encoders record the revolution data of its corresponding motor, which is stored by the DAQ and denoted by either a "0" or "1" in a dataset. Each encoder generates a time dataset along with two sets of square-wave data, denoted by "Encoder1_A" and "Encoder1_B." Dataset A can be used to determine the RPM of the corresponding motor, while dataset B is used to determine the direction in which the motor is spinning (clockwise or counter-clockwise).

To determine the RPM, the user must create a program that takes the "Encoder1_A" data and locates the rising edges. Rising edges are the location in the data set where consecutive values go from "0" to "1." This increase in encoder value denotes the rising edge of a square wave and can therefore be used to determine the time between square waves. Once this "Delta T" has been determined, the motor's frequency (Hz) is calculated by the following equation, where "360" denotes the number of encoder pulses per revolution of the motor.

$$Motor\ Frequency\ (Hz) = \frac{1}{Delta\ T\ \times\ 360}$$

The RPM of the motor can then be calculated by multiplying the motor frequency by "60", where "60" denotes the number of seconds in a minute:

$$RPM = Motor\ Frequency\ \times\ 60$$

2.3 Fast-Fourier Transform Noise Analysis

The raw data stored by the DAQ device does not provide an accurate insight into each motor's average thrust and torque generation. As seen by monitoring LabVIEW during testing, considerable amounts of frequency noise are present in this data. An analysis of the noise frequency is required to determine whether the data should be run through a low or high-pass filter.

While there are multiple approaches to performing noise analysis, the approach used for this thesis was a Fast-Fourier Transform (FFT). Running datasets, as an array, through FFT in MATLAB transforms the data from the time domain to the frequency domain. Once the data is in the time domain, the next step is to determine the amplitude of the frequencies. This can be done by taking the absolute value of each data point and normalizing it by the length of the frequency domain array. Since complex conjugates represent the values in the frequency domain, only the portion from zero to positive infinity is needed for the noise analysis, which can be isolated by only considering the first half of normalized data.

The range of frequencies can then be determined by multiplying the sampling frequency by the length of half of the normalized array, where the sampling frequency denotes the number of samples taken per second from a continuous signal. For example, in MATLAB notation:

$$FrequencyRange = SamplingFrequnecy \times \frac{\left(0:\left(\frac{L1}{2}\right)\right)}{L1}$$

When plotted on a logarithmic scale with the amplitude (Newtons) on the “y” axis and frequency (Hertz) on the “x” axis, a large spike will be present at 0 Hertz. This spike is referred to as the DC Component of the frequency domain and represents the average of the signal over a period. The DC component can therefore be removed by subtracting the mean of the data to be run through FFT from itself while the dataset is still in the time domain [7]. For example, in MATLAB notation:

$$Thrust = Thrust - mean(Thrust)$$

Once the DC component is removed from the dataset, the remaining noise will be characterized by peaks over the frequency range. The correctness of the approach can be confirmed by ensuring that there is a large spike at the frequency corresponding to the RPM of the motor. Once the FFT results are validated, analysis of the amount of low and high-frequency noise present can be used to determine the type of filter needed to clean up the data’s signal. In the case of this thesis, there were large amounts of high-frequency noise present in the data signals (as seen below in Figure 4), so it was concluded that the use of a low-pass filter was required.

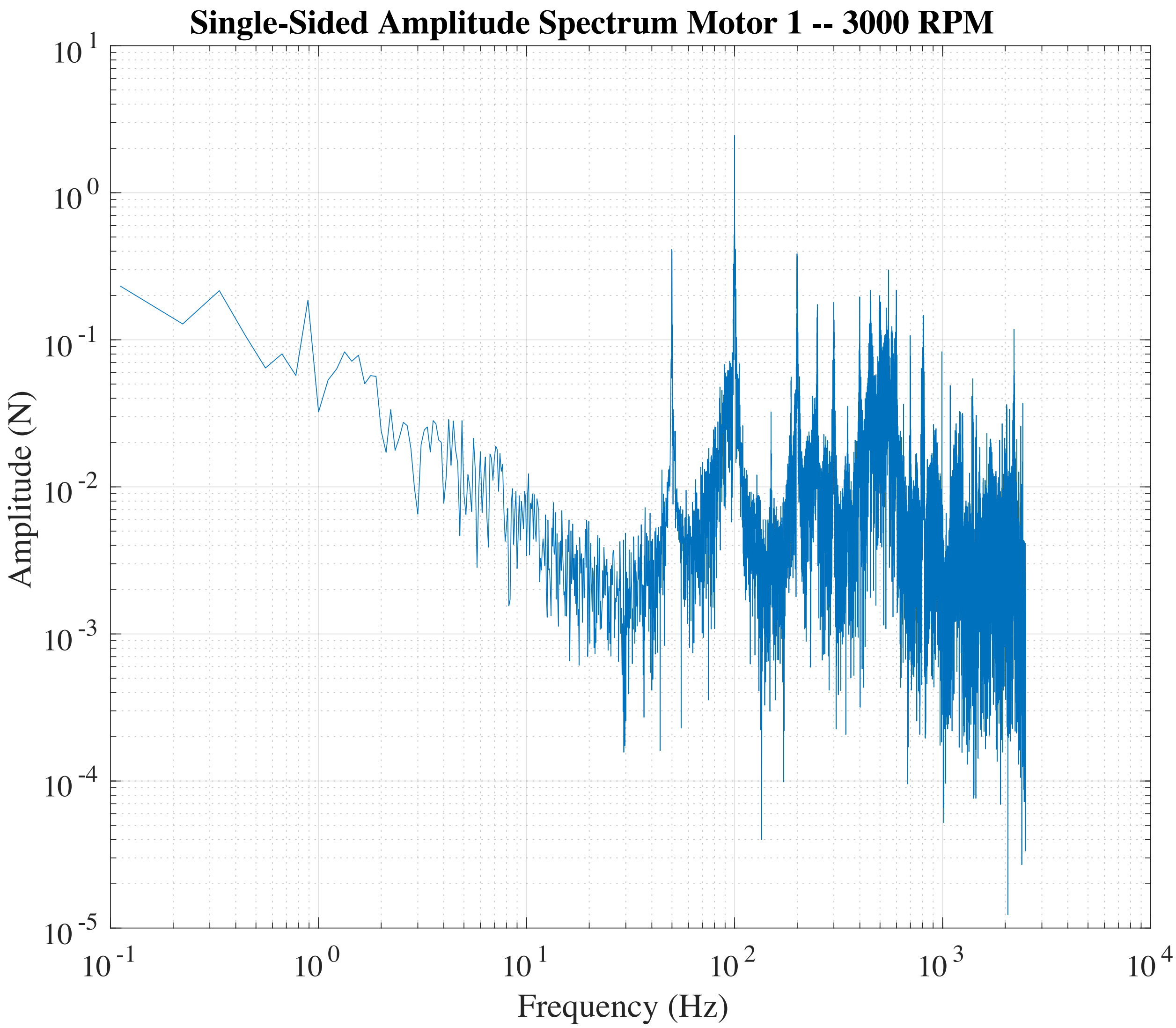

Figure 5. Unfiltered FFT Noise Analysis of Motor 1 at 3000 RPM

2.4 Application of Low-Pass (Butterworth Filter)

Multiple types of low-pass filters can be applied to clean up data signals during post-processing. For example, moving-window averages in MATLAB are considered a form of a low-pass filter and are often used to clean up signals with primarily high-frequency noise. However, for the data reviewed by this thesis, it was deemed more effective to use a Butterworth filter. A Butterworth Filter is a type of low-pass filter that requires a normalized cutoff frequency and filter order as parameters. It does not allow any noise at a frequency higher than the cutoff point to pass through the filter, effectively removing all high-frequency noise from the signal.

The user determines the cutoff frequency, and, in the case of this thesis, it was set to be half of the motor's RPM frequency. This cutoff prevents the RPM frequency and blade-pass frequency from being included in the data, which was necessary since the blades used in our testing were not balanced.

The filter order represents the degree of the approximating polynomial employed by the filter. Typically, the larger the order, the closer the filtered result will be to the ideal Butterworth Frequency. For this thesis, a 2nd order filter was used, which is considered a low-order filter. There were negligible differences between 2nd and 3rd order filtered results, so the 2nd order filter was selected due to a higher filter roll-off rate being unnecessary.

Running data through a Butterworth Filter can introduce a delay in the signal, which essentially means that the output signal is no longer aligned with the input signal, with respect to time. This delay is not always uniform and is often most prominent at the beginning of a filtered signal. This initial data can be neglected to prevent skewing the average of the filtered data. MATLAB also offers the zero-phase "filtfilt" command, which filters forwards and backward through the data to prevent it from unevenly shifting as it is filtered [10]. Both methods were employed while processing the data used in this thesis to prevent signal delay after applying the Butterworth filter.

To further prevent large spikes in the data after filtering, any data points that were greater/less than the summation/subtraction of two times the standard deviation and mean of the data were set equal to the summation of two times the standard deviation and mean of the data. Although this step did prevent large spikes as intended, it had relatively little effect on the final averages of the data. For example, if a spike is past the defined limits, the following command would occur in MATLAB notation:

$$Thrust = mean(Thrust) + (2 \times std(Thrust))$$

Ideally, the application of a low-pass Butterworth filter would result in a perfectly flat thrust production curve. However, this is not what happens for most data signals. Acceptable data filtering results in a curve that, while not perfectly constant, only experiences minor fluctuations in the signal.

After filtering was completed, each motor's thrust signal for a particular separation distance did not vary by more than 2.5 newtons. Likewise, the torque signal generated by each motor did not vary by greater than 0.15 newton meters. These ranges were deemed acceptable for the purpose of this research.

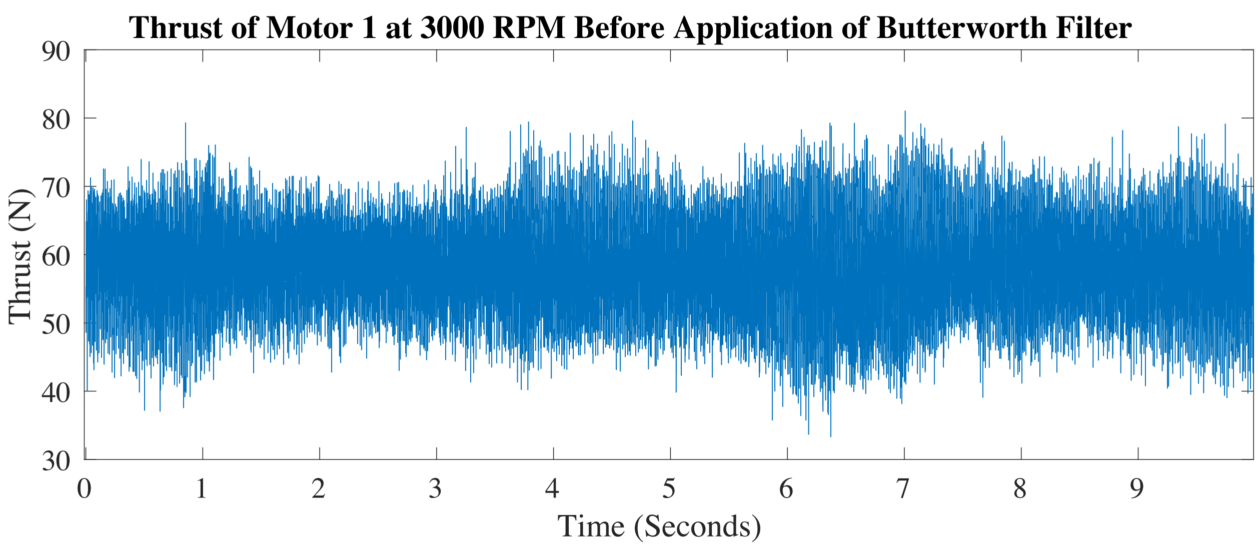

Figure 6. Thrust Signal of Motor 1 at 3000 RPM Before Filtering

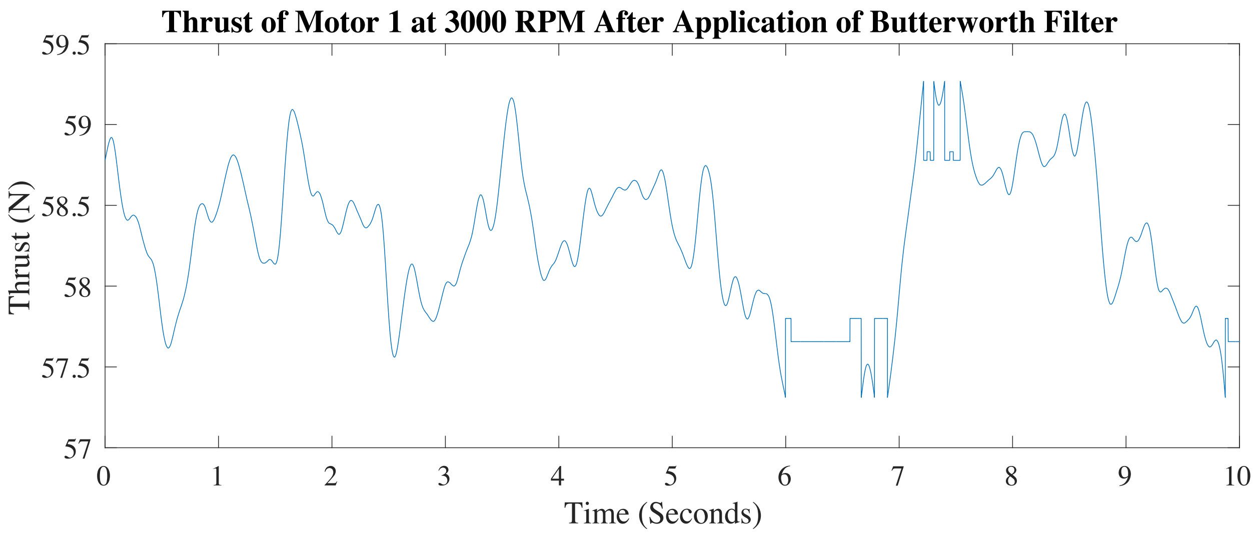

Figure 7. Thrust Signal of Motor 1 at 3000 RPM After Filtering

Chapter 3. Results and Discussion

After completing the post-processing filtering, the accumulated data was sorted by RPMs of 2000, 2500, and 3000. These RPMs will be expressed as percentages of the maximum operational RPM, denoted as the "operational RPM," for the KDE Direct 8218xf-120 motor, which is 3500 RPM within this testing environment. In the following graphs, motor 1 represents the top blade, while motor 2 represents the bottom blade in the coaxial rotor system. The curve titled "total" represents the summation of the thrust production by both motors in the coaxial rotor system. The uncertainty bars shown at each blade separation distance for the motor 1 and motor 2 curves represent the standard deviation in thrust generation. Note that the line connecting the experimental data points for each curve was generated using a "spline" function that did not alter the fixed experimental points. Although this does not match typical practice for experimental data, the point connections were included to ensure easy visualization of the curves.

The following sections of the thesis will analyze how varying blade separation distance affected both the thrust and torque generated by the motors in the coaxial rotor system. Additionally, the aerodynamic performance of each individual motor will be compared to the performance of that same motor in an isolated, single-rotor system. The goal of the analysis is to determine if altering the system's blade separation distance results in different levels of aerodynamic interference between the rotors, which corresponds to an improvement or reduction in the overall aerodynamic performance of the system.

3.1 Thrust with Respect to Blade Separation Distance

3.1.1 Thrust Generation at 2000 RPM (57% of Operational RPM)

At a steady state of 57% of the operational RPM for both motor 1 and motor 2, there did seem to be a correlation between separation distance and aerodynamic performance of the coaxial rotor system with respect to thrust levels. As seen below in Figure 8, there are four distinct regions of fluctuation in aerodynamic thrust generation between the motors over the range of 2.7” to 27” blade separation distance.

Region 1 begins at the 10% separation distance and extends to the 30% mark. A large sinusoidal spike in thrust generation from motor 1 and a sharp decreasing trough in thrust generation from motor 2 characterize the region. In Figure 8, the highlighted section within this region represents an area of optimized performance by motor 1, where it outperforms its isolated, single-rotor system thrust production.

Region two ranges from separation distances of 30% to 60%, with motor 1 experiencing a 4-newton sinusoidal improvement in thrust generation, accompanied by a further decreasing trough and then increasing thrust generation from motor 2. The highlighted section within this region again represents a key area of optimized motor 1 thrust performance. However, this peak in motor 1’s thrust production is far more pronounced than the one previously noted in Region 1.

Region 3 begins at a 60% blade separation distance and spans to a separation distance of 80%. Region 4 stretches from 80% to 100% blade separation distance. Both Region 3 and Region 4 demonstrate increasing curves in the thrust generation from motor 1, accompanied by troughs in motor 2’s thrust production. The continued sinusoidal fluctuation in thrust performance by the motors suggests that there exists some form of aerodynamic interference created by the top rotor that, while boosting its own performance, has impairing effects on the bottom rotor of the coaxial system. However, neither Region 3 nor Region 4 contain sections where motor 1 demonstrated the ability to outperform its isolated results, as seen in the first two regions.

Despite both motors initially producing approximately 24 newtons of thrust at a blade separation of 10%, the differential between motors ultimately increased by 16.66% of their initial production at a separation distance of 100% (27”). The inability of both motors to recover to their isolated thrust performance suggests that the interactions between the rotors are still present at a blade separation distance of 100%.

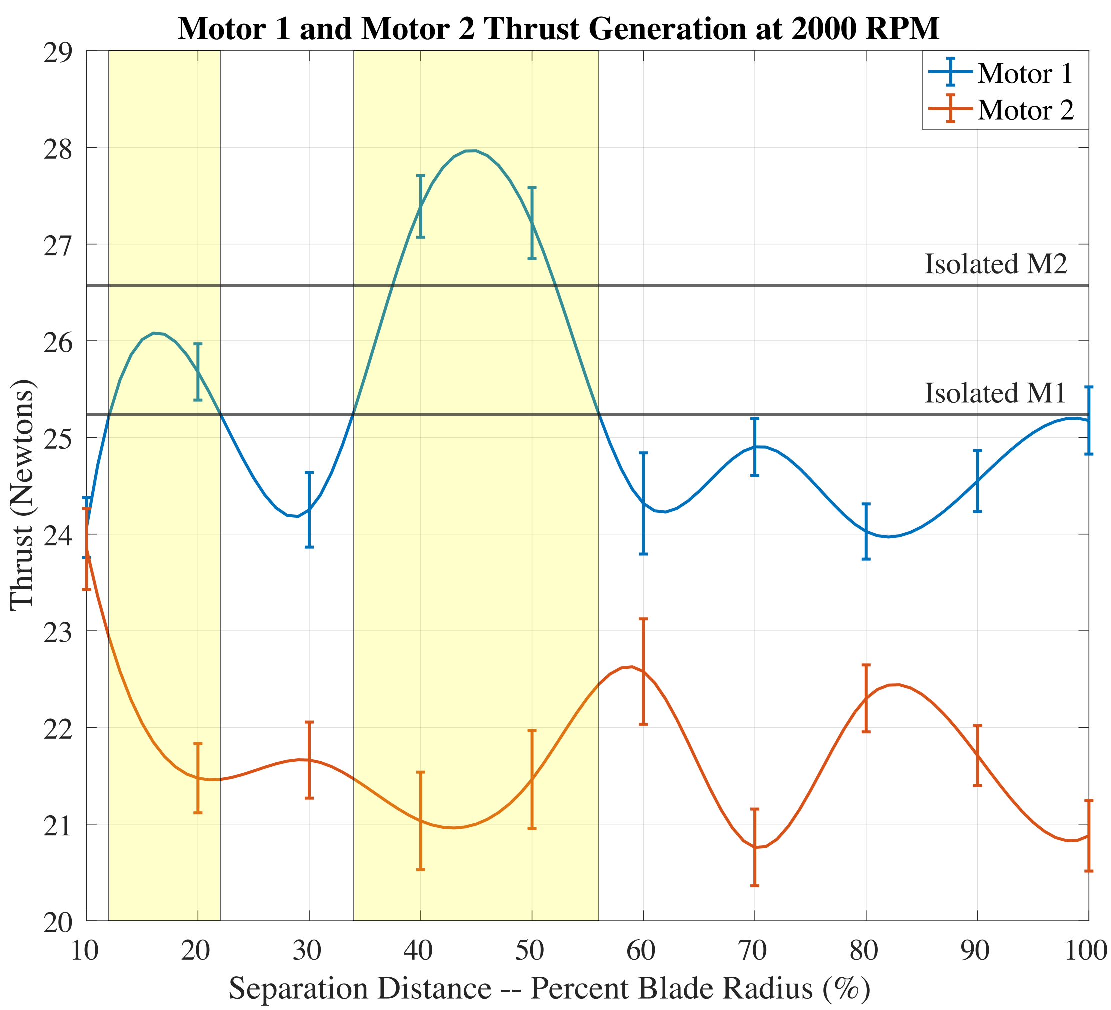

Figure 8. Motor 1 and Motor 2 Thrust Generation at 2000 RPM

The summation of both motors' thrust generation provides a mean total of 46.94 newtons of thrust. While the total thrust does not vary by more than 8.5% of the mean total over the tested separation distances, Figure 9 demonstrates that the peaks in total thrust correspond closely with the optimized peaks in motor 1's thrust production. Said relationship suggests that motor 1's thrust generation is the dominating factor in the coaxial system's overall thrust performance.

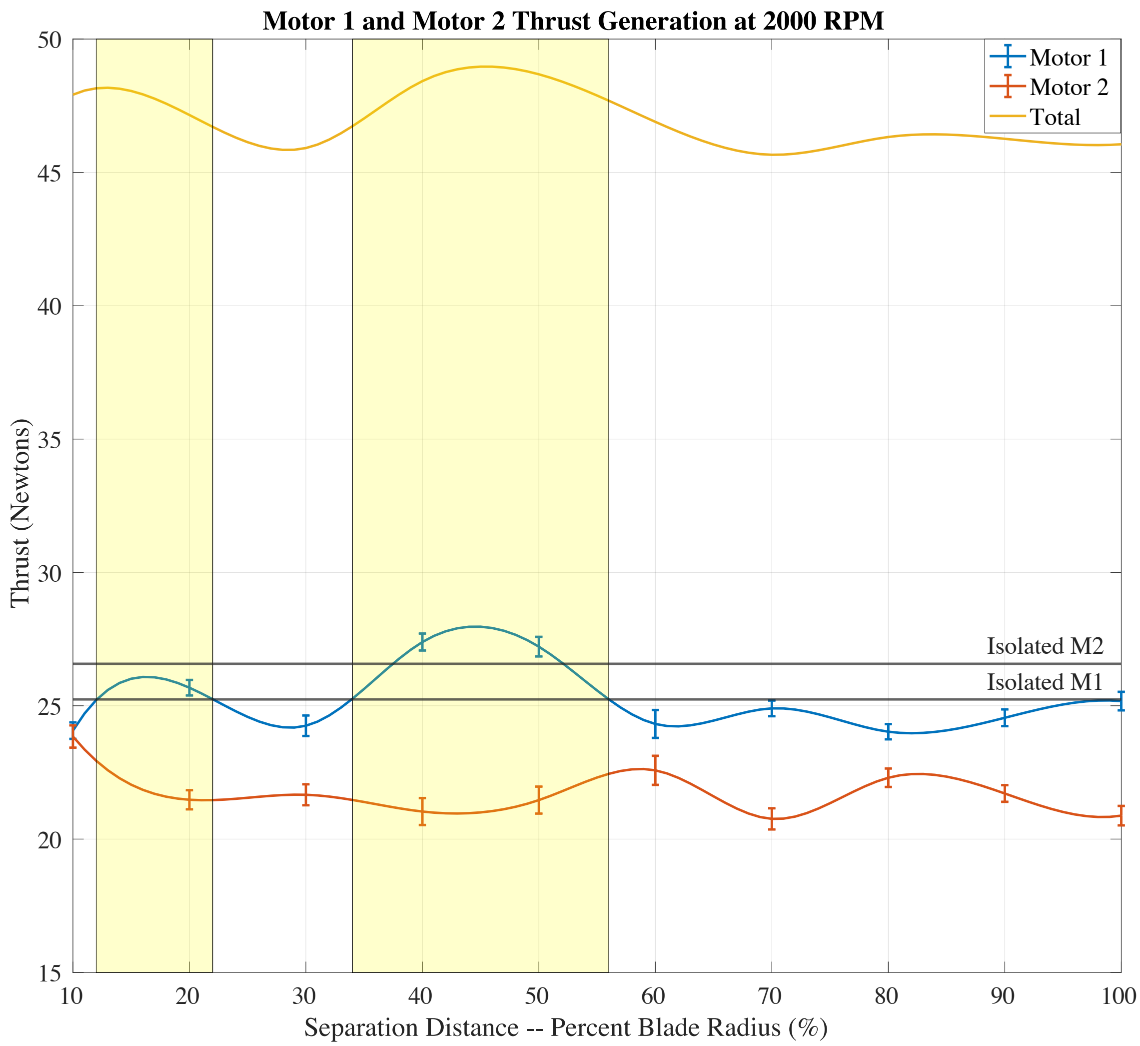

Figure 9. Summation of Motor 1 and Motor 2 Thrust Generation at 2000 RPM

As previously discussed, Figure 8 demonstrates that in two different blade separation regions (i.e., 12.5%- 22.5% and 37.5%-52.5%), motor 1 outperforms its isolated, single-rotor system thrust production. These regions suggest that operating a coaxial rotor system at an RPM of 2000 optimizes the thrust generation of motor 1 at certain blade separation distances. The maximum thrust production for motor 1 occurs around the 45% blade separation distance mark, where it outperforms its isolated results by approximately 10.26%. This blade separation distance also represents the location of peak thrust performance by the overall system. Therefore, the region represents the most efficient separation distance for a coaxial rotor system when operated at 57% of the operational RPM.

3.1.2 Thrust Generation at 2500 RPM (71% of Operational RPM)

At a steady state of 71% of the operational RPM for both motor 1 and motor 2, the correlation between separation distance and change in the aerodynamic performance of the coaxial rotor system was less pronounced than that seen at a steady state of 57% of the operational RPM. As seen below in Figure 10, there are only three regions of thrust generation patterns between the motors over the range of a 2.7” to 27” blade separation distance. At 10% blade separation, motor 1 produces 40.28 newtons of thrust, and motor 2 produces 35.19 newtons of thrust. This difference of approximately 13.48% is far greater than the differential of 1.04% demonstrated at 57% of the operational RPM at the same blade separation distance.

Region 1 begins at a separation distance of 10% and extends to the 40% mark. A gradual hump in the thrust generation of motor 1 and a corresponding but not proportional valley in the thrust generation of motor 2 characterize Region 1. It should be noted that the highlighted section of optimized performance seen at blade separation distances of 12.5% to 22.5% at 57% of the operational RPM is no longer present, as motor 1 does not manage to outperform its isolated results in this region at 71% of the operational RPM.

Region 2 spans from a separation distance of 40% to the 60% mark. This region demonstrates a sinusoidal peak in the thrust generation from motor 1, accompanied by a large valley in the thrust generation of motor 2. The amplitude of motor 1's peak is approximately 7.17% of its isolated thrust level, while the amplitude of motor 2's valley is around 4.67% of its isolated level. In Figure 10, the highlighted section within Region 2 represents an area of optimized performance by motor 1, where it outperforms its isolated, single-rotor system thrust production.

Region 3 begins at a separation distance of 60%, continues until the 100% mark, and shows both motors following a relatively steady curve with slight deviations of no more than 1.18% of the average isolated thrust level. At a 100% separation distance, motor 1 generates 40.81 newtons of thrust, which is 1.3% greater than at the 10% mark. However, motor 2 finishes with a thrust generation of 32.3 newtons, which is a loss of 8.56% from its 10% separation mark. Therefore, while motor 1 began to return to its isolated thrust production value, motor 2 was unable to recover to even its 10% level within a blade separation distance of 100%. The cumulation of these factors suggests that while increasing the separation distance past 60% of blade diameter has reduced effects on the system's performance at 71% of the operational RPM, motor 2 still experiences performance-impairing aerodynamic interference from motor 1 at a 100% separation distance.

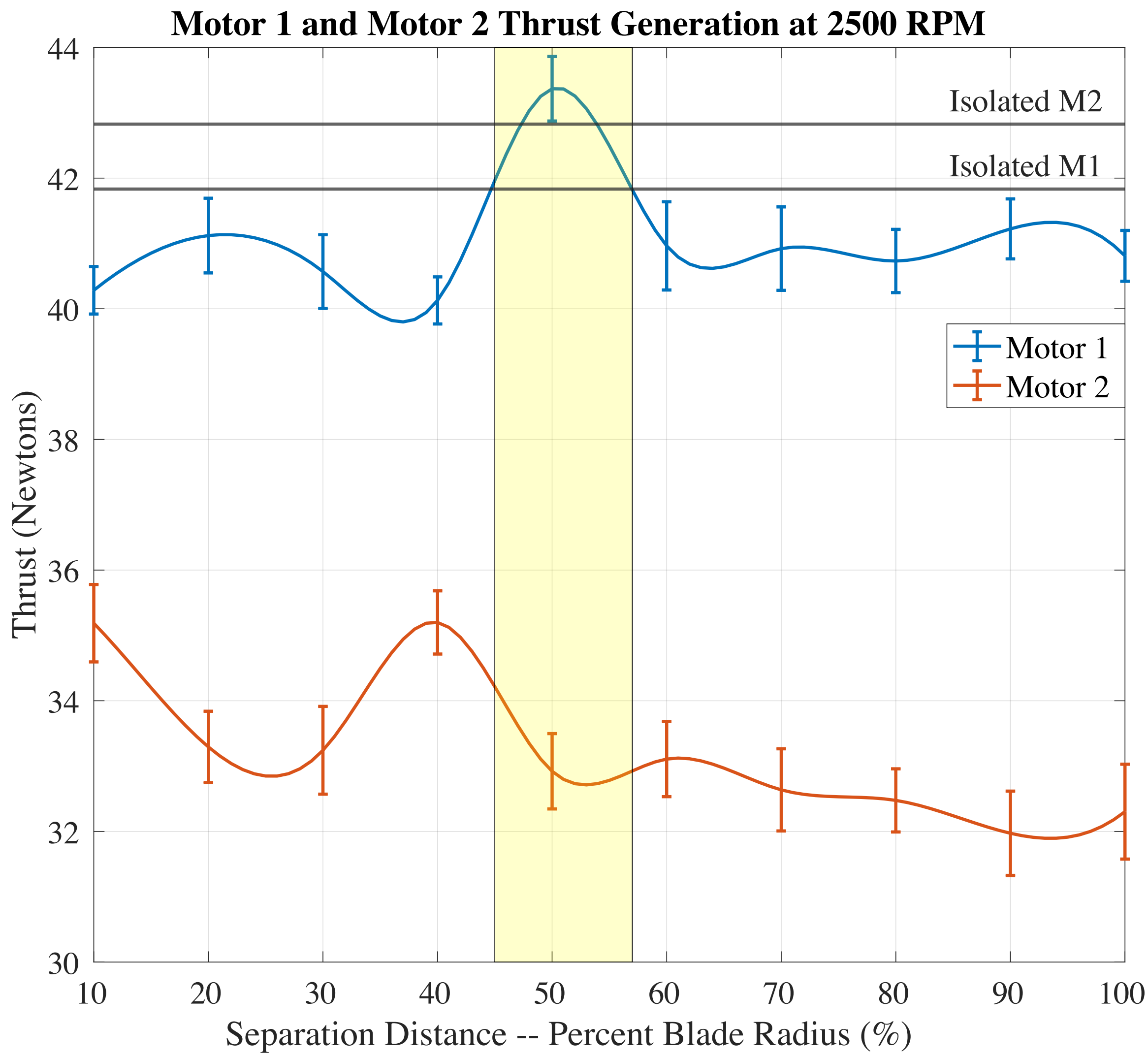

Figure 10. Motor 1 and Motor 2 Thrust Generation at 2500 RPM

The summation of both motors' thrust generation provides a mean total of 74.24 newtons of thrust. While the total thrust does not vary by more than 4.04% of the mean total over the range tested, Figure 10 demonstrates that the lone peak in total thrust again corresponds with the optimized peak in motor 1's thrust production. This trend in improved total thrust production further suggests that motor 1's thrust generation is the dominating factor in the coaxial rotor system's overall thrust performance.

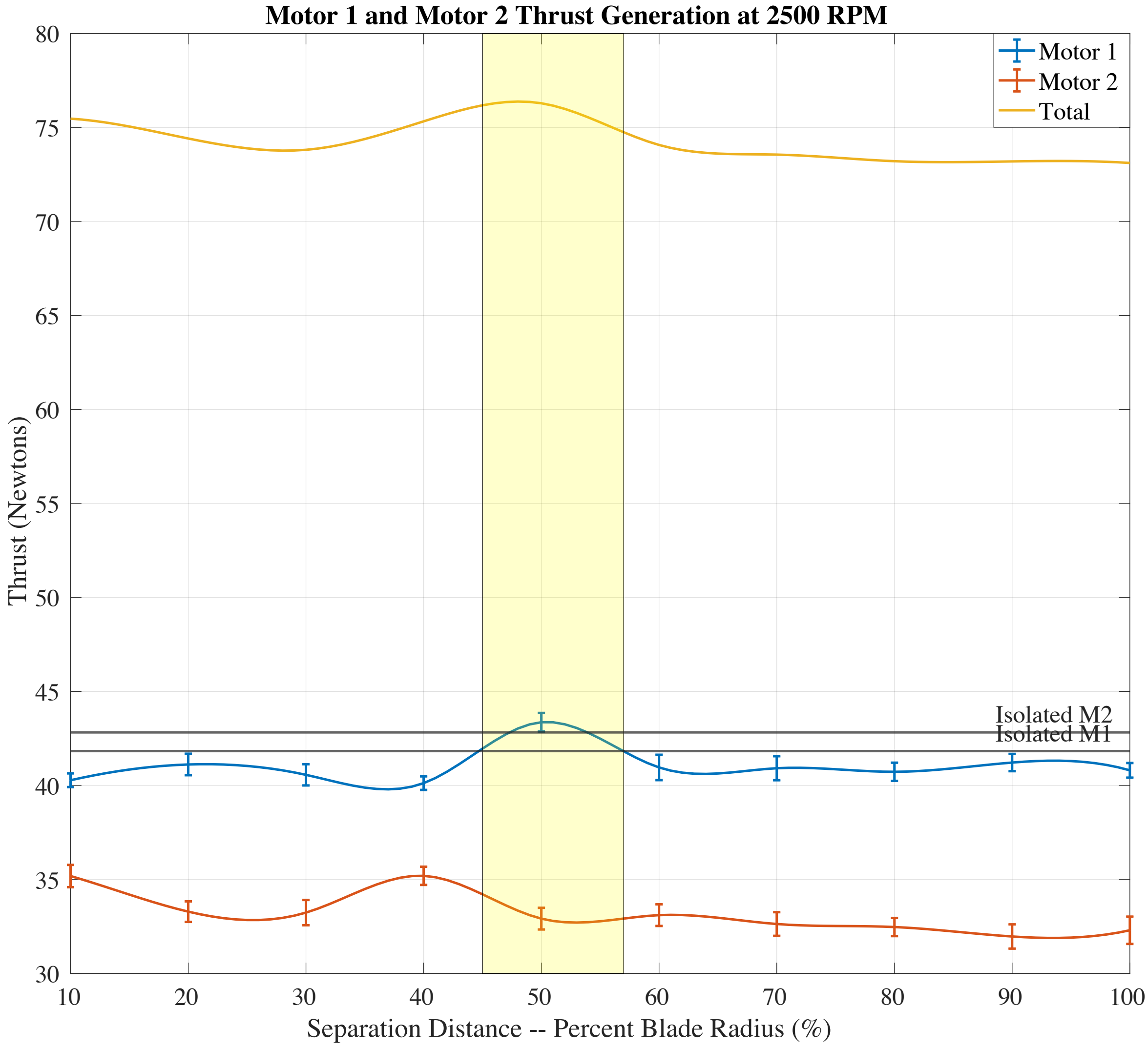

Figure 11. Summation of Motor 1 and Motor 2 Thrust Generation at 2500 RPM

As previously discussed, Figure 10 shows that at 71% of the operational RPM, there is a blade separation region where motor 1 outperforms its isolated, single-rotor system thrust production. However, the less-pronounced region seen at 57% of the operational RPM has disappeared, and the larger region appears to have reduced in magnitude and shifted. There is now only one region (i.e., 45%-57.5%) where the coaxial system elevates the thrust generation of motor 1 above its isolated results, and its largest outperformance occurs at a blade separation distance of 50%. At said separation distance, motor 1 outperforms its isolated results by approximately 3.61%. Additionally, the maximum total thrust production for the system again coincides with this region of optimized motor 1 thrust generation, which suggests that the 50% mark represents the most efficient blade separation distance for a coaxial rotor system when operated at 71% of the operational RPM.

3.1.3 Thrust Generation at 3000 RPM (86% of Operational RPM)

At a steady state of 86% of the operational RPM for both motor 1 and motor 2, the relationship between blade separation distance and change in the aerodynamic performance of the coaxial rotor system is notably less prevalent than for 57% and 71% of the operational RPM. As seen below in Figure 12, there are four regions of thrust generation levels between the motors over the range of 2.7" to 27" blade separation distance. At 10% blade separation, motor 1 produces 57.19 newtons of thrust, while motor 2 produces 50.40 newtons of thrust, resulting in a difference of 12.62%.

Region 1 begins at a separation distance of 10% and ends at the 20% mark. A gradual increase in the thrust generation of motor 1 and a much sharper decrease in the thrust generation of motor 2 characterize this region. Region 2 ranges from 20% to 50% and is defined by a relatively steady thrust generation level from motor 1, accompanied by an initially steady, then gradual, increase in the thrust generation of motor 2. It is worth noting that despite the 2.58% increase in motor 2's thrust generation at the end of this region, there is no corresponding decrease in the thrust performance of motor 1. Neither Region 1 nor Region two have a section where motor 1 outperforms its isolated levels.

Region 3 stretches from 50% to 80% separation distance and is comprised of another gradual increase in motor 1's thrust performance and a gradual decrease in motor 2's thrust production. Although motor 1 does not manage to outperform its isolated thrust production values in this region, the curve does approach the isolated level. This hump could represent the optimized peak previously seen at a separation distance range of 45% to 57.5% for 71% of the operational RPM after it has shifted and reduced in magnitude.

Region 4 begins at 80% and ends at 100% and demonstrates a rapid decrease in the thrust generation of motor 1, accompanied by an equally rapid increase in the thrust generation of motor 2. At the final tested distance of 100% blade separation, motor 1 records a thrust generation of 56.17 newtons, and motor 2 records a thrust generation of 49.70 newtons. These thrust levels suggest that at 86% of the operational RPM, a blade separation distance of 100% does not allow the motors to recover to their isolated thrust production levels, but they do almost return to their 10% separation distance production levels. Said recovery would require minimal aerodynamic interference between the rotors.

Ultimately, Figure 12 no longer demonstrates a blade separation region where motor 1 outperforms its isolated, single-rotor system thrust production. These regions of motor 1 optimization were most distinguishable at 57% of the operational RPM, then reduced and shifted at 71% of the operational RPM and have completely disappeared at 86% of the operational RPM. This trend suggests that a coaxial rotor system’s thrust performance depends on RPM at low rotational speeds but becomes independent of RPM at higher rotational speeds.

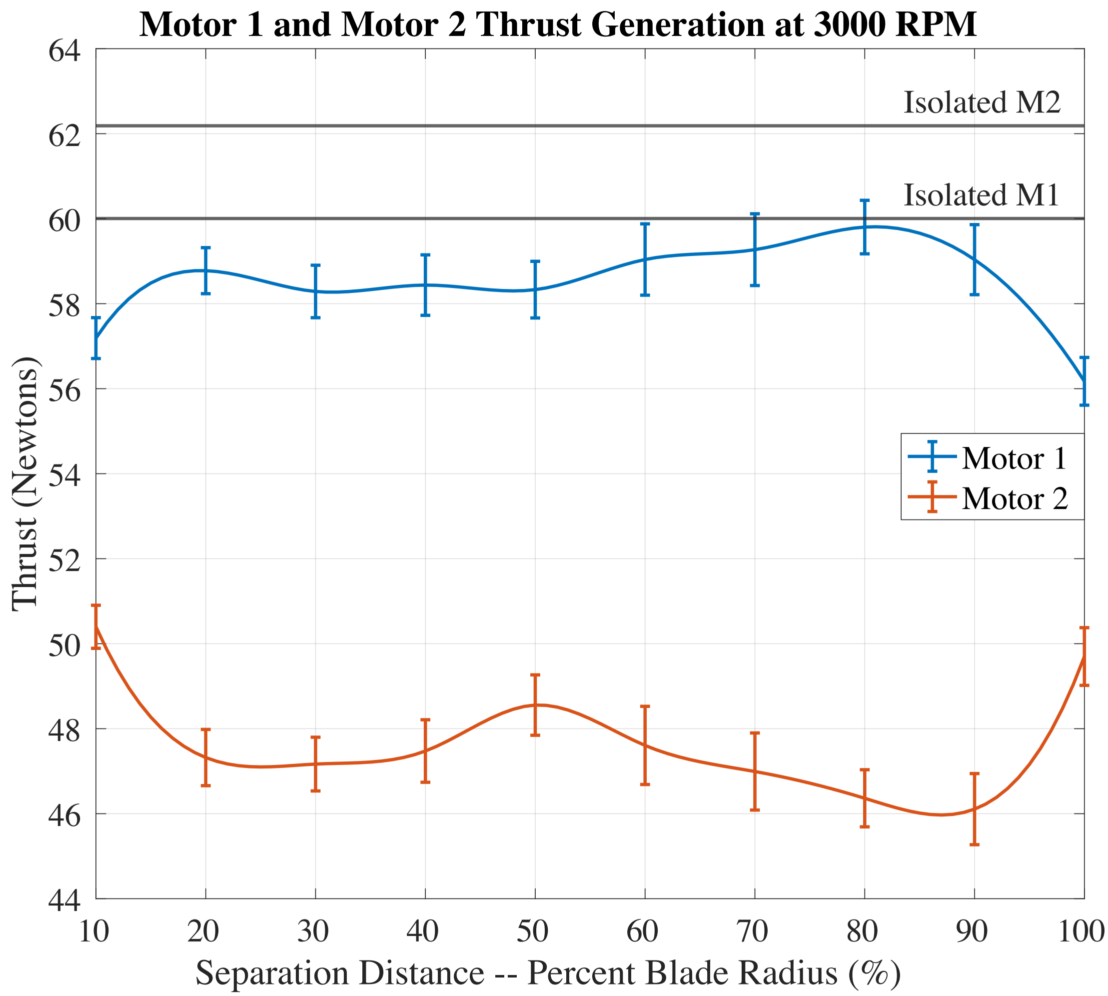

Figure 12. Motor 1 and Motor 2 Thrust Generation at 3000 RPM

The summation of both motors' thrust generation provides a mean total of 106.11 newtons of thrust. The total thrust does not vary by more than 1.88% of the mean total over the tested separation distances. As shown in Figure 13, no distinct troughs or valleys are present in the thrust production of either motor 1 or motor 2. Therefore, the previously mentioned relationship between motor 1's thrust production and the coaxial system's overall thrust performance appears to depend on operational RPM, as it disappears at high RPMs.

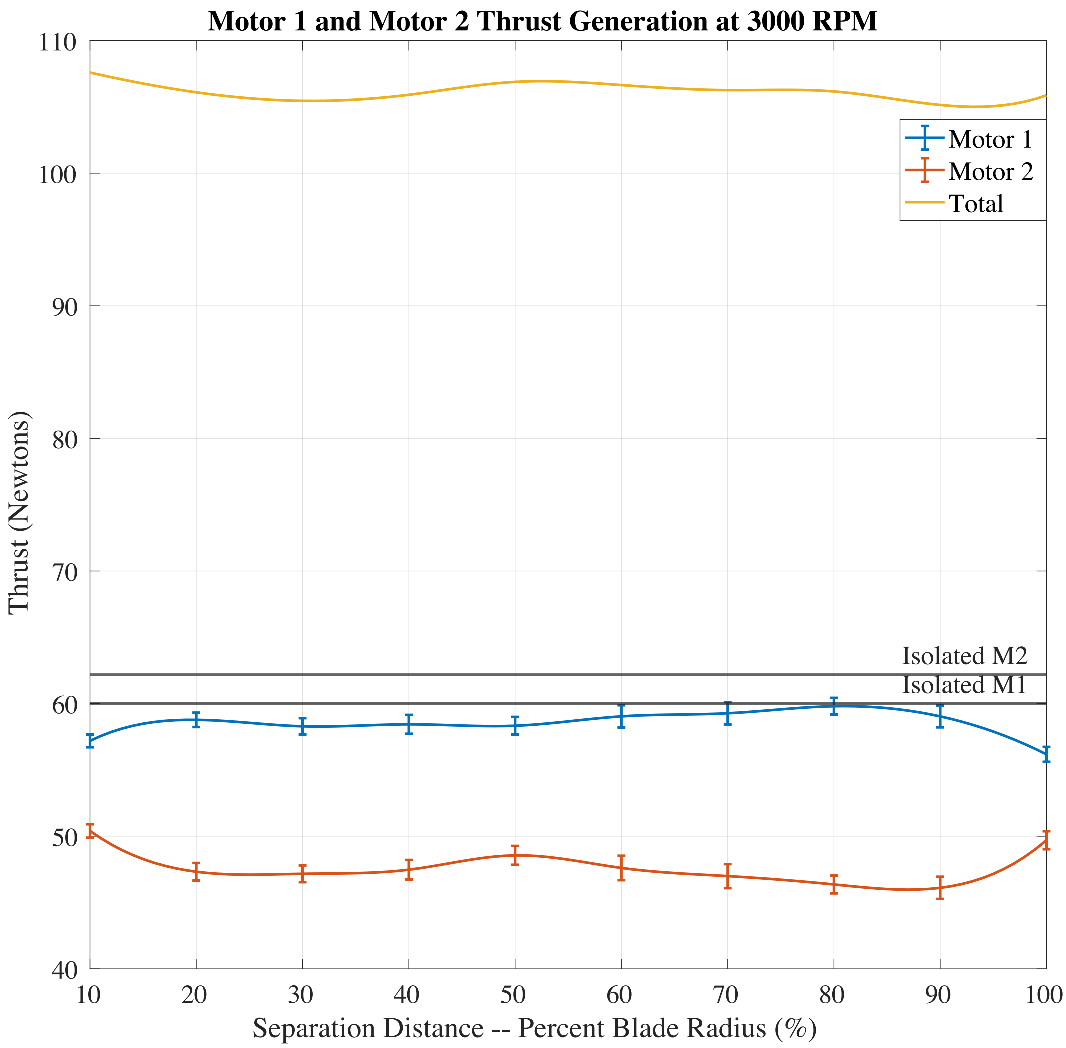

Figure 13. Summation of Motor 1 and Motor 2 Thrust Generation at 3000 RPM

3.2.1 Verification of Thrust Signals Via Unfiltered Data

The raw data was processed and plotted to verify the accuracy of the filtered thrust curves at all three tested RPMs. For the highlighted sections of optimized motor 1 performance to be considered credible, the unfiltered data must also demonstrate these peaks in the thrust performance curves at 57% and 71% of the operational RPM. Therefore, Figures 14-16 were analyzed to determine if the location of the optimized humps occurred at the same blade separation distance and to ensure that the standard deviation bars followed the curve. If the standard deviation bar curves maintained a linear line over the tested blade separation distances, and the highlighted peaks fell within this range, the data would not be considered viable. In this scenario, the humps in the data could not be proven to represent anything more than standard deviation fluctuations in a potentially linear thrust signal.

However, Figures 14, 15, and 16 all demonstrate standard deviation curves that follow the overall pattern of the thrust signals. The standard deviation bars correlating to the highlighted sections maintain an average standard deviation approximately equal to those at other blade separation distances but still increase to create the hump in optimized performance. Additionally, the raw thrust signals show the optimized humps at the same blade separation distances as the filtered thrust signals for all tested RPMs. The cumulation of these two supporting factors verifies the credibility of the optimized motor 1 performance sections displayed in the filtered data.

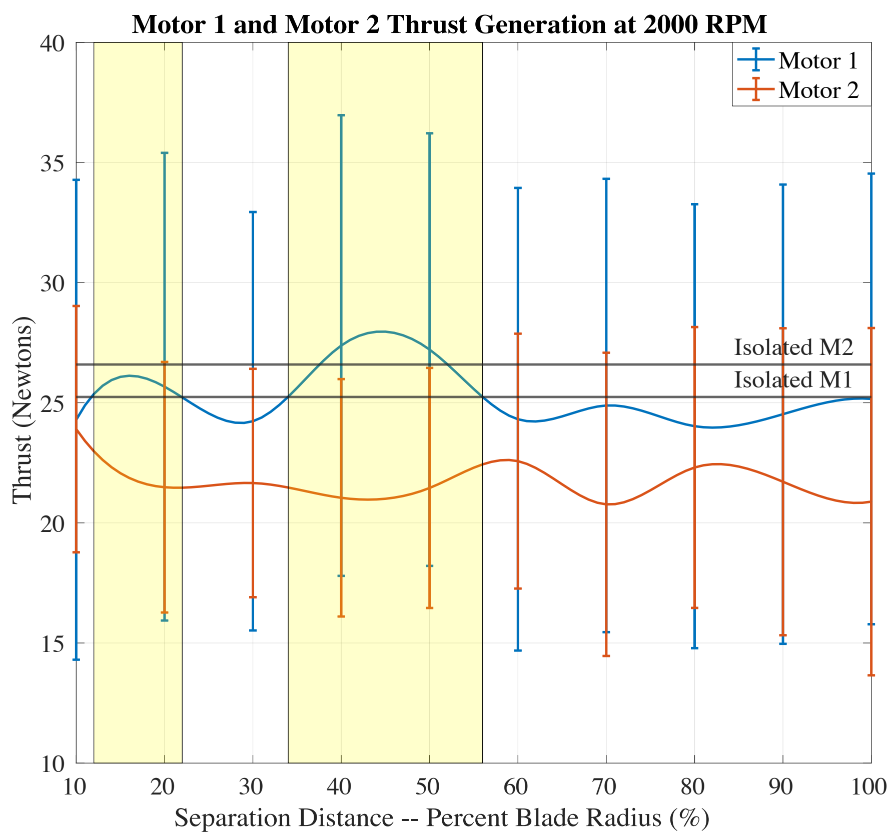

Figure 14. Raw Motor 1 and Motor 2 Thrust Generation at 2000 RPM

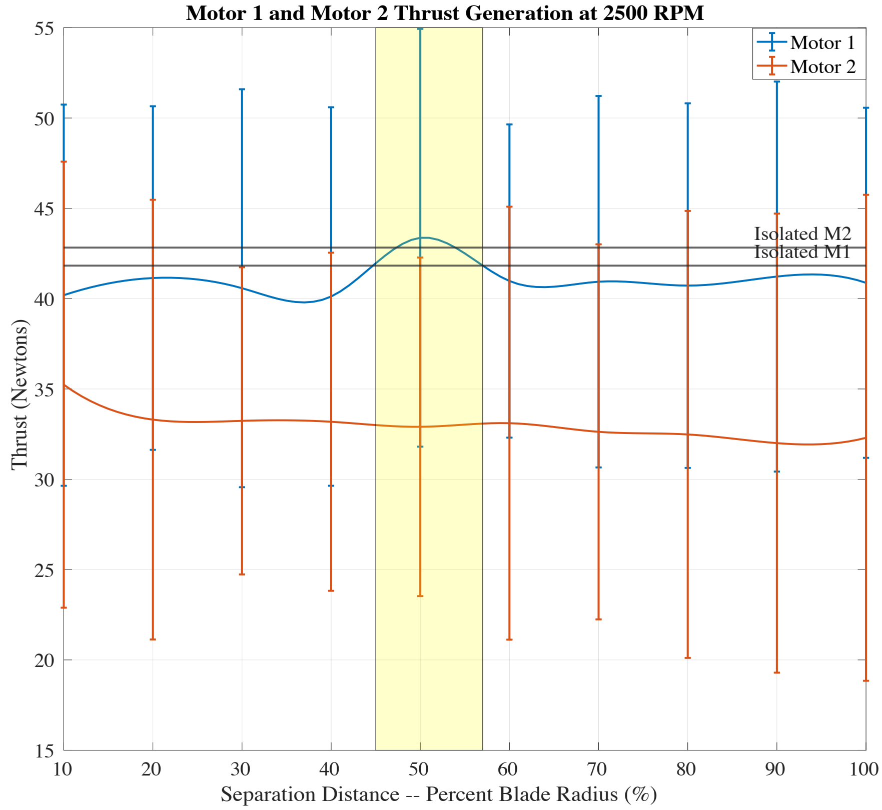

Figure 15. Raw Motor 1 and Motor 2 Thrust Generation at 2500 RPM

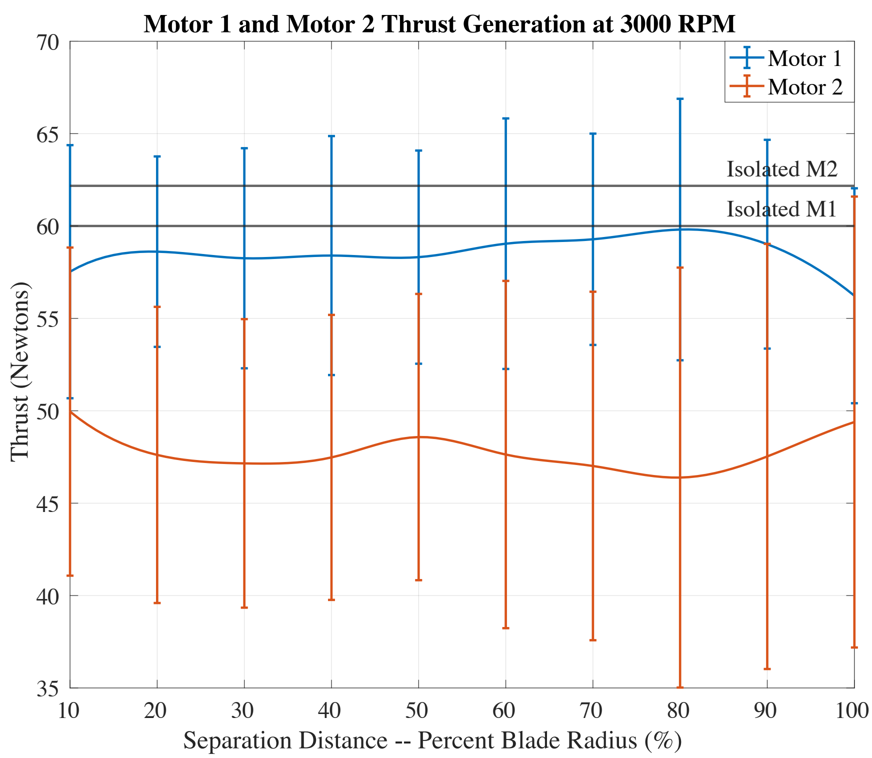

Figure 16. Raw Motor 1 and Motor 2 Thrust Generation at 3000 RPM

3.2 Torque with Respect to Blade Separation Distance

3.2.1 Torque Generation at 2000 RPM (57% of Operational RPM)

At a steady state of 57% of the operational RPM for motor 1 and motor 2, there seemed to be a correlation between blade separation distance and the aerodynamic performance of the coaxial rotor system with respect to torque levels. Figure 17 represents the absolute magnitude of both motors' torque production, and the highlighted regions correspond to the optimized thrust regions discussed in Section 3.1.1. As seen in Figure 17, the slight rises in the torque generated by one motor are often accompanied by slight decreases in the torque generated by the other motor. However, despite these slight increases and decreases in torque generation by the two motors, neither experience deviations larger than 5.8% of their respective isolated torque production.

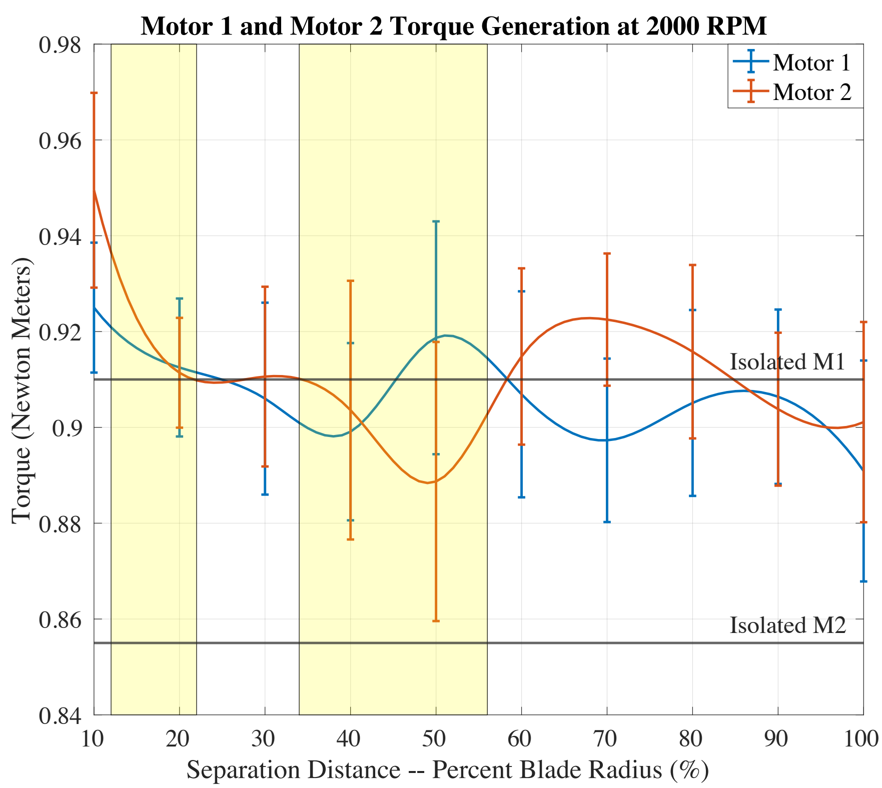

Figure 17. Motor 1 and Motor 2 Torque Generation at 2000 RPM

Figure 18 shows that motor 1 experiences a positive torque generation, while motor 2 experiences a negative torque generation. This sign difference matches intuition, as the testing used a counter-rotating coaxial rotor system, so it is expected for the torque generated by the motors to be inverted. The slight increases in total torque generation by the system within the highlighted regions support the findings discussed in Section 3.1.1 regarding increased thrust production of the overall coaxial rotor system due to optimized performance.

When operated at 57% of the operational RPM, both motors generated torques with a magnitude of approximately 0.9 newton meters, allowing for said canceling of the generated torques. It should be noted that motor 2's torque generation over the tested separation distances increases slightly from its isolated, single-rotor system results, allowing it to seemingly synchronize with the magnitude of motor 1's torque production. A summation of both motors' torque generation provides a mean total of -0.004 newton meters of torque, which is negligible and can be neglected. Therefore, the results at 57% of the operational RPM support the idea that coaxial rotor systems do not require a torque-stabilizing tail system, as the torque generation of the overall coaxial rotor system effectively cancels out.

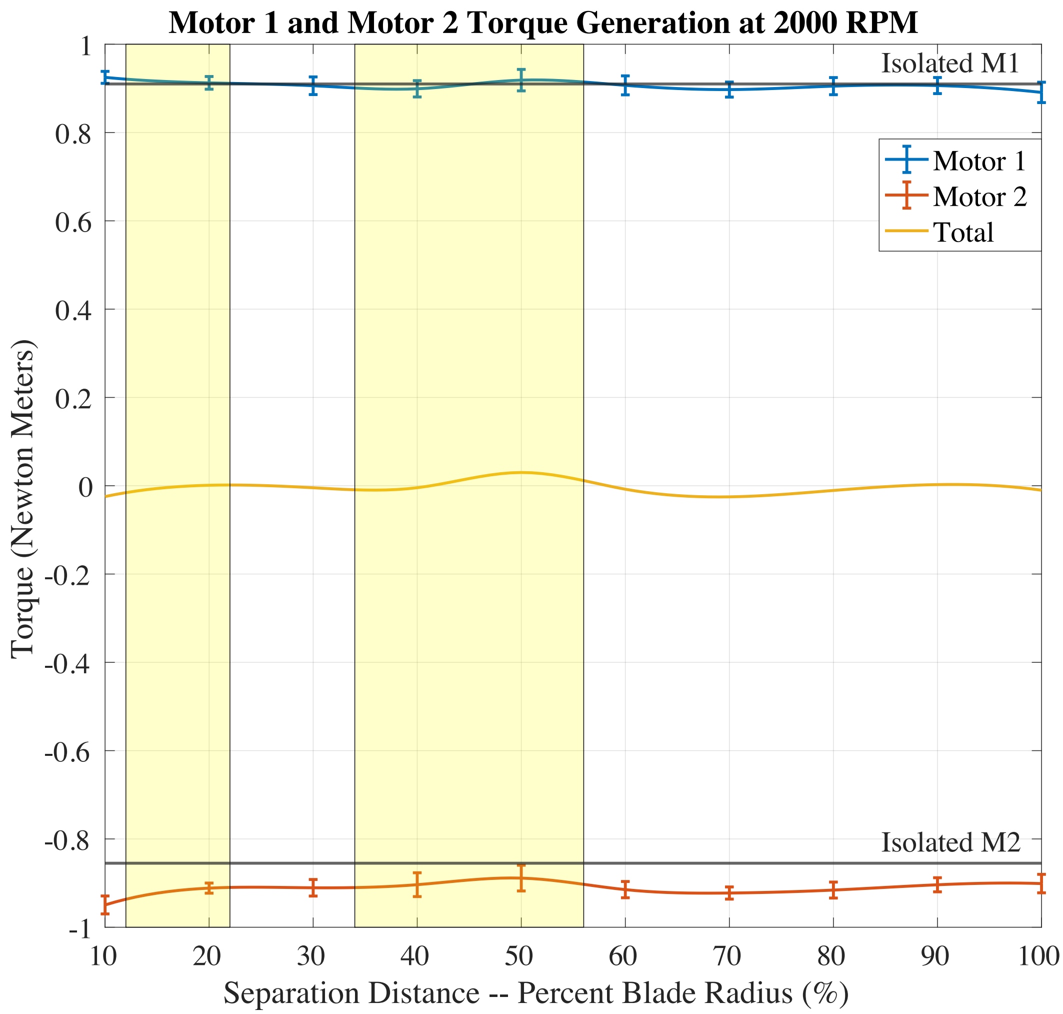

Figure 18. Summation of Motor 1 and Motor 2 Torque Generation at 2000 RPM

3.2.2 Torque Generation at 2500 RPM (71% of Operational RPM)

At a steady state of 71% of the operational RPM for both motors, Figure 19 shows that there again appears to be some correlation between blade separation distance and the torque generation by the two motors in the coaxial system. While slight increases in the torque generated by one motor are again accompanied by slight decreases in the torque generated by the other motor, the deviations in torque generation do not exceed 6.8% of their respective isolated torque levels.

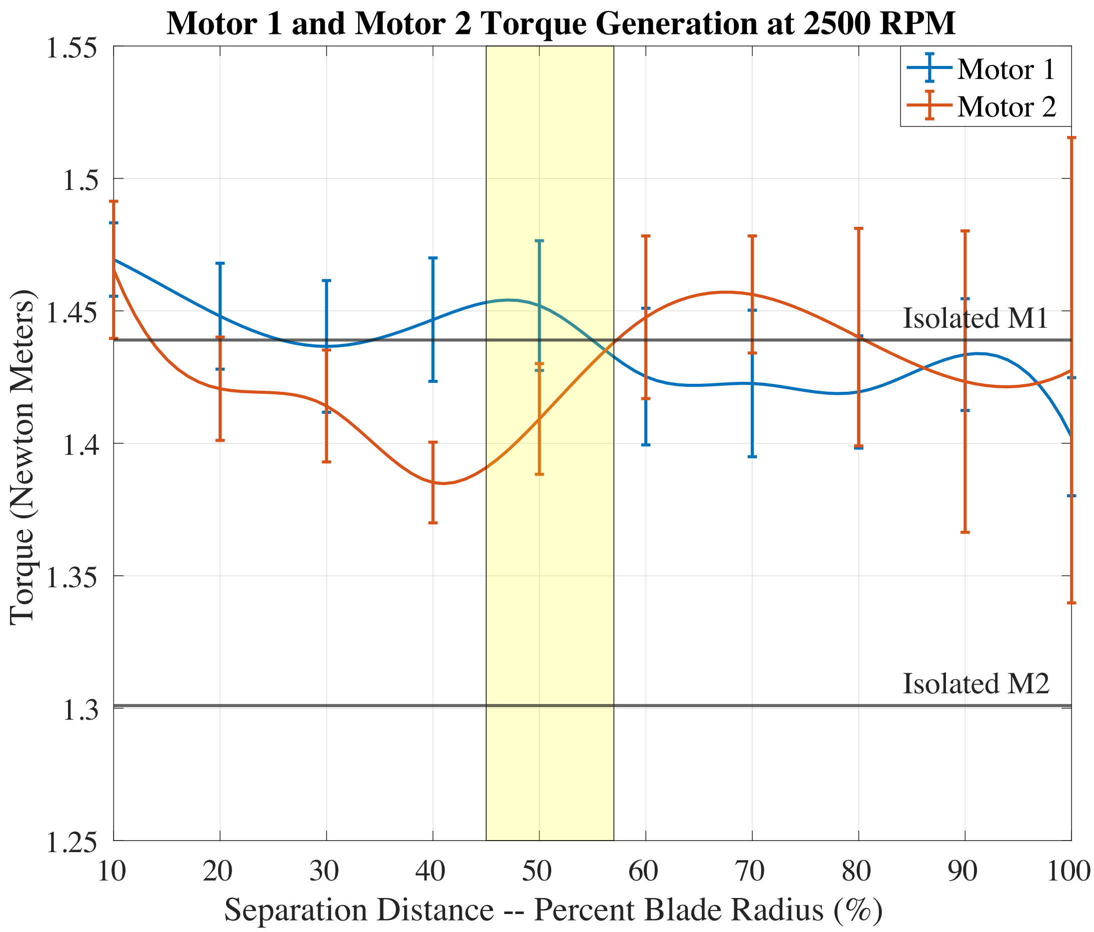

Figure 19. Motor 1 and Motor 2 Torque Generation at 2500 RPM

The highlighted region shown in Figure 20 corresponds to the optimized thrust region discussed in Section 3.1.2. Unlike the results discussed for 57% of the operational RPM, the total torque generation by the system appears to decrease throughout this region, despite the increased thrust production by the overall coaxial rotor system.

At 71% of the operational RPM, the torque generated by both motors has a magnitude of approximately 1.44 newton meters, with motor 2 again synchronizing to motor 1’s torque generation. The similarity of magnitude in opposing directions results in a negligible mean total torque generation of 0.011 newton meters, which supports the idea of the torque generated by a coaxial rotor system canceling overall.

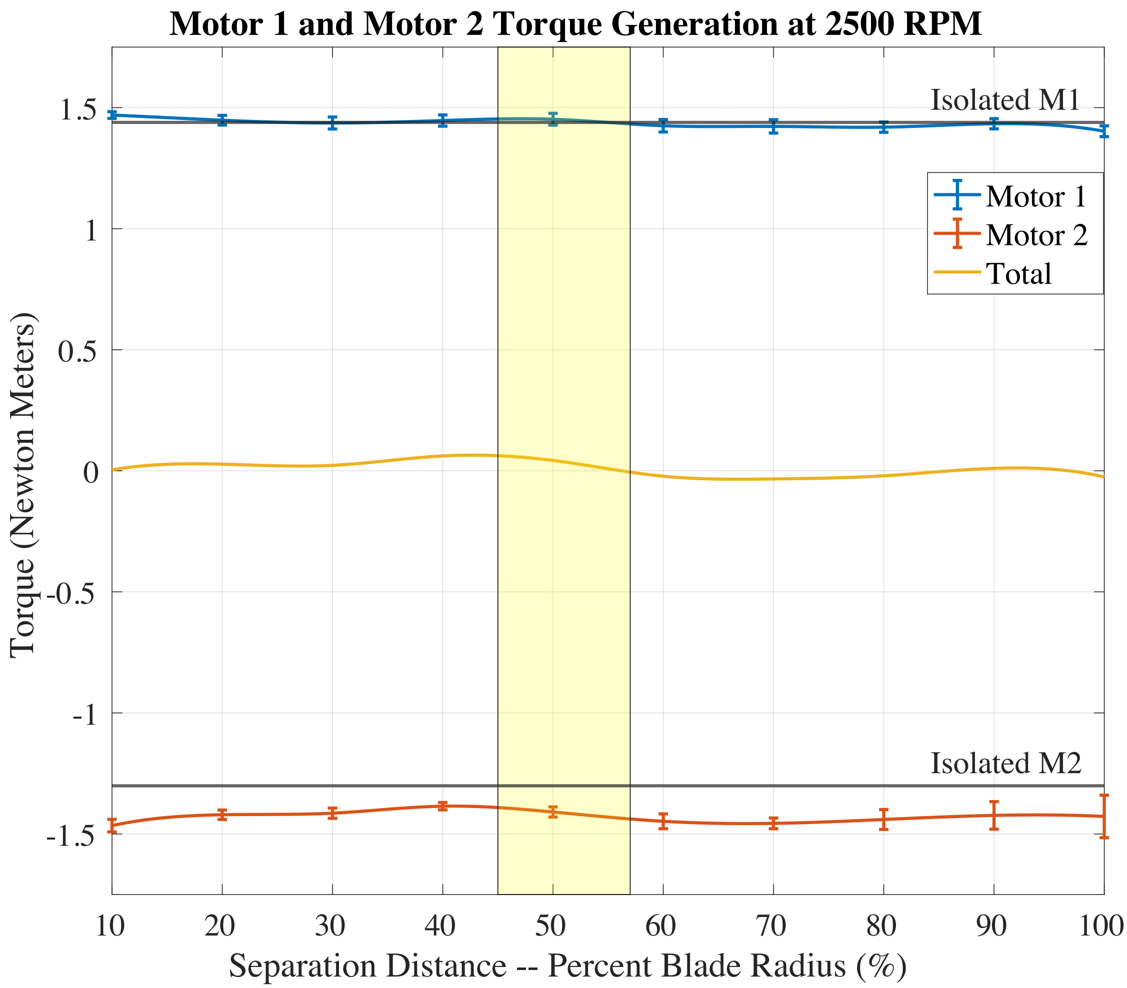

Figure 20. Summation of Motor 1 and Motor 2 Torque Generation at 2500 RPM

3.2.3 Torque Generation at 3000 RPM (86% of Operational RPM)

At a steady state of 86% of the operational RPM for both motors, the generation of torque by the motors in the coaxial rotor system now seems practically independent of changes in the blade separation distance. The adverse relationship between the torque generation of the two motors is present but difficult to distinguish, as referred to in Figure 21 and Figure 22. The aerodynamic interference between the two motors of the system is shown to have minimal effect on the torque generation of the motors.

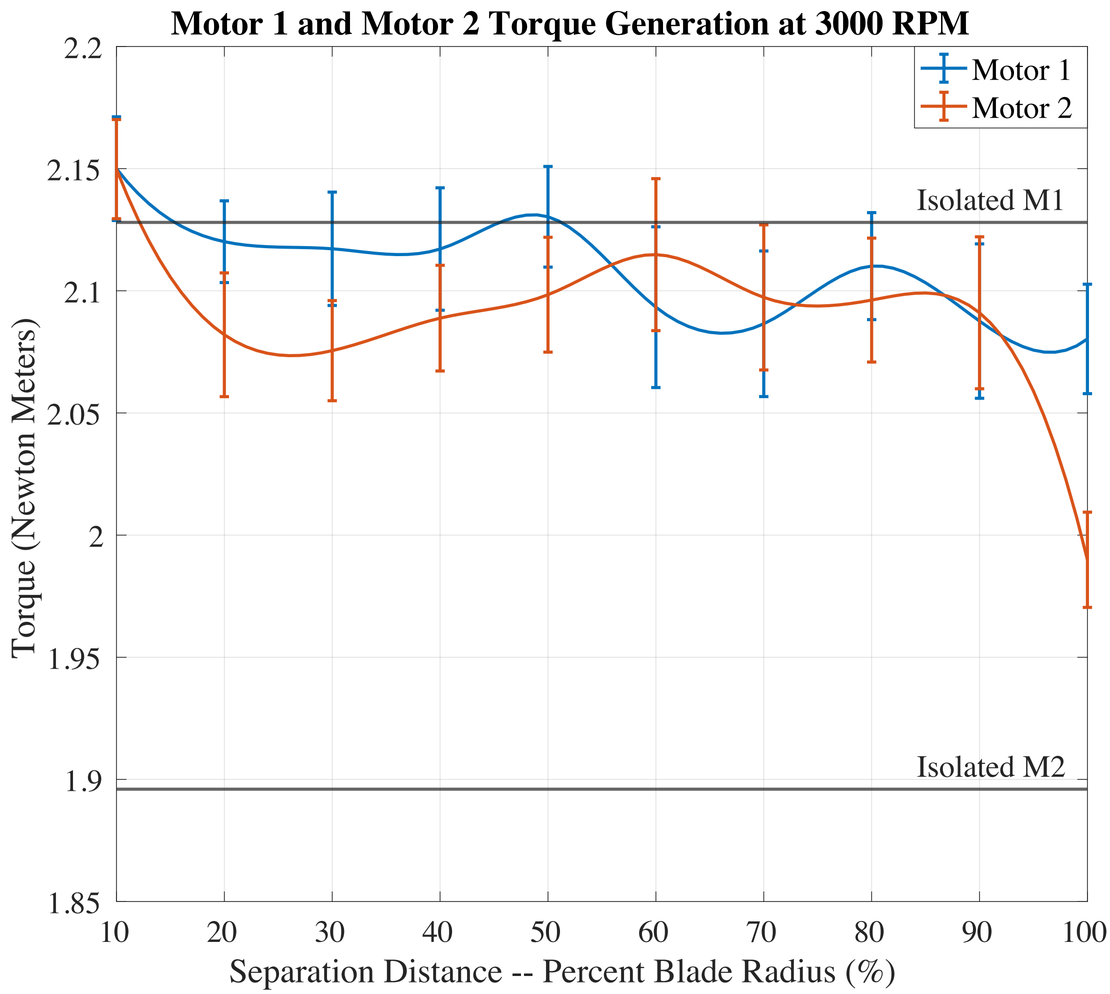

Figure 21. Motor 1 and Motor 2 Torque Generation at 3000 RPM

As with the previously tested RPMs, the magnitude of both motors' torque generation is approximately equal (in opposing directions), which is around 2.2 newton meters at 86% of the operational RPM. A summation of both motors' torque generations results in a mean total of 0.017 newton meters of torque and can be neglected, supporting the trend of overall torque cancellation in a coaxial rotor system.

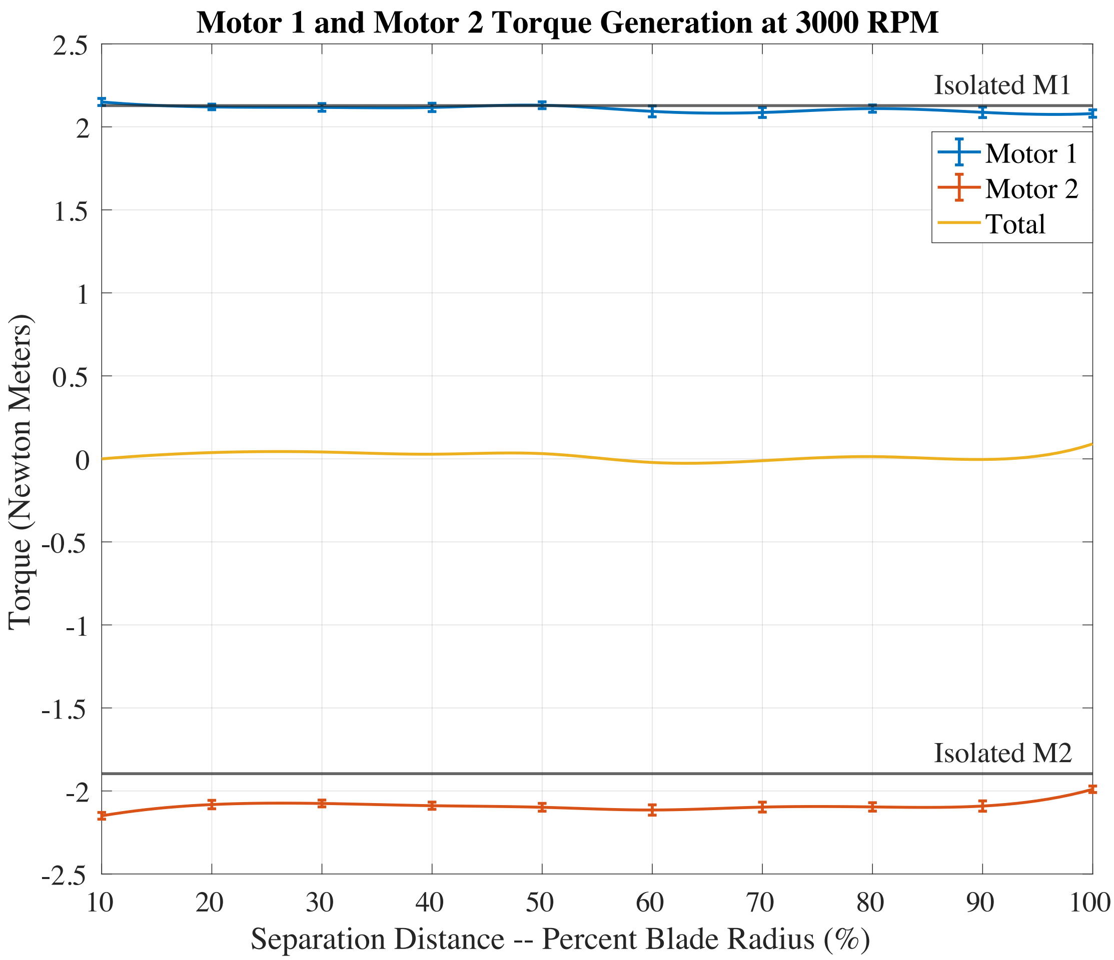

Figure 22. Summation of Motor 1 and Motor 2 Torque Generation at 3000 RPM

3.3 Comparison of Coaxial Rotors to Isolated Rotor

After completing the testing of the coaxial rotor system at separation distances ranging from 10% to 100% of the blade diameter (2.7” to 27”), both rotors were run individually to simulate an isolated, single-rotor system. Prior to these isolated tests, the blade not being spun was removed, so there would be no interference or effects of air hitting the still blade. During testing, it was ensured that both motors were fed the same power supply. This precaution should have prevented incidentally improved aerodynamic performance due to extra power available.

This testing design aimed to investigate at which points during the coaxial rotor testing one of the separate motors would produce thrust equivalent to the level it produced when tested as an isolated, single-rotor system. The theory behind this investigation was that at some large, arbitrary separation distance, both motors in the coaxial rotor system would be able to produce the same thrust that they did when tested individually.

Reaching this target data would suggest that when the separation distance becomes large enough, the motors in a coaxial rotor system would essentially act as two separate, isolated rotor systems. Therefore, the motors would no longer experience aerodynamic interference or interaction between the airflows generated running simultaneously. If this point of independence could be reached, it would offer thrust generation levels equivalent to two isolated systems, while requiring a much smaller area footprint due to the shared axis.

The following data is divided into tables separated first by motor, then by RPM. The separation distances shown are a function of the rotor blade diameter. The percent differences shown correspond to the data in the column to their left, compared to the respective isolated value.

3.3.1 Motor 1 Performance Vs. Isolated Motor 1 at 2000 RPM

At 57% of the operational RPM, motor 1 produced 25.238 newtons of thrust when operated as an isolated, single-rotor system. This value represents the presumed optimum thrust performance of motor 1 for this RPM in hover. However, as previously discussed in Section 3.1.1 and demonstrated in Table 1, there are two blade separation regions where motor 1 outperforms its isolated results at 57% of the operational RPM. These locations are denoted on the chart by a positive percent difference ranging from a 3.28% improvement to a 10.26% improvement from the isolated results.

While the thrust generated by motor 1 over the tested blade separation distances has previously been shown to fluctuate in a sinusoidal pattern (refer to Figure 8), Table 1 below provides insight into which regions the motor performed at a level comparable to its isolated results. At blade separations of 20% and 70%, motor 1 generated thrust levels within 2% of the isolated motor 1 system. At the 100% separation distance mark, motor 1 produced thrust within 0.25% of the isolated results. The production of a thrust level so close to that of the isolated value suggests that the 100% mark might represent the end of the region where motor 1's performance is affected by aerodynamic interferences and essentially becomes an isolated system on the same axis as motor 2. However, the fluctuation of percent difference for motor 1 shown from the 10% to 90% separation distance range suggests that these fluctuations are a function of both turbulent (dirty) airflow and blade separation distance.

At 57% of the operational RPM, motor 1 generated 0.910 newton meters of torque when tested as an isolated system. The data shown in Table 1 suggests that the torque of the upper rotor is much less susceptible to aerodynamic interference and separation distance effects. The largest percent difference from the isolated motor 1 occurs at the 10% mark, which is only 1.613% off the isolated value. The small 1% jumps in percent difference represent the slight increases in torque generated by motor 1 that were previously seen in Figure 17. It should also be noted that the percent differences for motor 1's torque production increase substantially at the separation distances corresponding to the largest optimized region of motor 1 thrust performance (i.e., 40%-50%).

Motor 1 Thrust and Torque Generation at 2000 RPM Based on Blade Diameter Percentages				
Separation Distance	**Thrust (Newtons)**	**Thrust Percentage Difference (%)**	**Torque (Newton Meters)**	**Torque Percentage Difference (%)**
10 %	24.067	-4.748	0.925	1.613
20 %	25.677	1.727	0.913	0.252
30 %	24.251	-3.989	0.906	-0.462
40 %	27.389	8.178	0.899	-1.227
50 %	27.217	7.546	0.918	0.929
60 %	24.317	-3.715	0.907	-0.363
70 %	24.902	-1.338	0.897	-1.427
80 %	24.027	-4.915	0.905	-0.562
90 %	24.549	-2.764	0.906	-0.418
100 %	25.175	-0.248	0.891	-2.143
Isolated	25.238	0.00	0.910	0.00

Table 1. Motor 1 Thrust and Torque Generation at 2000 RPM -- Coaxial Vs. Isolated

3.3.2 Motor 2 Performance Vs. Isolated Motor 2 at 2000 RPM

At 57% of the operational RPM, motor 2 generated 26.574 newtons of thrust when operated as an isolated, single-rotor system. This value is 5.16% greater than motor 1’s isolated thrust at the same RPM. This implies that motor 2 is slightly more efficient when operated as an isolated system than motor 1 (despite all variables being controlled equally), which was not ideal for analyzing the results. However, the expected trends are still easily visible from the Table 2 data, as the sinusoidal pattern demonstrated in Figure 8 for motor 2 is apparent.

A key pattern discernable from the coaxial rotor system data and the respective isolated system data is that motor 2's thrust production within the coaxial rotor system is significantly more impaired than that of motor 1. Motor 2's percent difference in thrust generation between the coaxial system and the isolated value ranges from 10.818 % to 24.572%, which is a much larger deviation than that of motor 1 at the same RPM. The increased deviation makes sense from an aerodynamic standpoint. The airflow fed into the lower rotor (motor 2) during testing would have already transitioned to turbulent flow due to motor 1, creating a "dirty" air supply. This significant impairment of motor 2's thrust production does not improve as the separation distance increases, suggesting that aerodynamic interference is still present over the tested range. However, the lowest percent difference for motor 2 (i.e.,10.818%) occurs at a blade separation distance of 10%. This outlier performance at 10% may be due to the turbulent airflow created by motor 1 not yet having time to fully disperse and separate into sporadic flows due to the close proximity of the blades (i.e., 2.7 inches). Overall, the large percent differences in thrust generation for motor 2 compared to motor 1 supports the claim that improvements in motor 1 performance have degrading effects on the performance of motor 2.

At 57% of the operational RPM, motor 2 produced a magnitude of 0.855 newton meters of torque when ran as an isolated, single-rotor system. Table 2 demonstrates that the range of torque generation percent differences experienced by motor 2 over the tested separation distances span from 3.877% to 10.486%, translating to a maximum deviation of 0.094 newton meters.

Furthermore, the smallest percent difference in torque production for motor 2 occurs at the 50% mark, as opposed to the 10% mark for thrust; further suggesting that torque generation is not significantly impacted by aerodynamic inference.

While the torque values generated by motor 2 during the coaxial system testing appear almost equal to those generated by motor 1 during the same testing (as shown in Figure 17), motor 2's isolated value is slightly lower. This discrepancy is likely a result of the same testing imperfection that caused the difference in isolated thrust values between the two motors. However, according to the data below, motor 2 generates slightly higher torque values than motor 1 while operated within the coaxial system, when compared to their respective isolated system results. This synchronization of torque generation within the coaxial system's two motors demonstrates that the lower rotor of a coaxial system experiences degradations in torque performance, allowing it to reach a level that matches motor 1's torque generation.

Motor 2 Thrust and Torque Generation at 2000 RPM Based on Blade Diameter Percentages				
Separation Distance	**Thrust (Newtons)**	**Thrust Percentage Difference (%)**	**Torque (Newton Meters)**	**Torque Percentage Difference (%)**
10 %	23.847	-10.818	-0.949	10.486
20 %	21.475	-21.224	-0.911	6.398
30 %	21.662	-20.365	-0.910	6.309
40 %	21.033	-23.279	-0.904	5.539

50 %	21.462	-21.283	-0.889	3.877
60 %	22.578	-16.259	-0.915	6.769
70 %	20.759	-24.572	-0.922	7.607
80 %	22.301	-17.488	-0.916	6.879
90 %	21.710	-20.147	-0.904	5.561
100 %	20.879	-24.002	-0.901	5.262
Isolated	26.574	0.00	-0.855	0.00

Table 2. Motor 2 Thrust and Torque Generation at 2000 RPM -- Coaxial Vs. Isolated

3.3.3 Motor 1 Performance Vs. Isolated Motor 1 at 2500 RPM

At 71% of the operational RPM, motor 1 generated 41.832 newtons of thrust when operated as an isolated single-rotor system. As previously discussed in Section 3.1.2 and demonstrated in Table 3, motor 1 outperforms its isolated system thrust performance by 3.61% at a blade separation distance of 50%. This improved performance by motor 1 is denoted by a positive percent difference but is 6.65% less than that seen at 57% of the operational RPM.

Referring to Table 3, the small sinusoidal peaks and valleys demonstrated in Figure 10 are visible in the percent difference data over the range of separation distances tested. However, there are regions where the thrust generated by motor 1 was within 2% of the isolated value (i.e., 20% and 90%). The 20% region’s small percent difference likely represents the shifted and magnitude-reduced optimized performance hump seen in motor 1’s thrust data at an RPM of 2000. Unlike at 57% of the operational RPM, the percent difference of motor 1 thrust’s production at a separation distance of 100% is not the closest region to the isolated value, as it is

2.663% worse. This suggests that a region where motor 1 fully recovers and acts as an isolated system is not within a 27” separation distance for 71% of the operational RPM.

At 71% of the operational RPM, motor 1 generated 1.439 newton meters of torque when operated as an isolated, single-rotor system. Table 3 again shows percent difference values of no more than 2.597% from the isolated values for motor 1, with six of the ten tested distances being less than a 1% difference. The closest torque generation to the isolated value comes at the 30% mark, with a percent difference of 0.188%. The data further collaborates with the findings that torque generation for an upper rotor is not a significant function of aerodynamic interference due to blade separation distance at 71% of the operational RPM.

Motor 1 Thrust and Torque Generation at 2500 RPM Based on Blade Diameter Percentages				
Separation Distance	**Thrust (Newtons)**	**Thrust Percentage Difference (%)**	**Torque (Newton Meters)**	**Torque Percentage Difference (%)**
10 %	40.283	-3.773	1.469	2.069
20 %	41.120	-1.716	1.448	0.603
30 %	40.569	-3.064	1.437	-0.188
40 %	40.128	-4.159	1.447	0.513
50 %	43.367	3.604	1.452	0.878
60 %	40.962	-2.101	1.425	-0.984
70 %	40.921	-2.203	1.423	-1.167

80 %	40.731	-2.667	1.419	-1.392
90 %	41.223	-1.467	1.433	-0.404
100 %	40.809	-2.476	1.402	-2.597
Isolated	41.832	0.00	1.439	0.00

Table 3. Motor 1 Thrust and Torque Generation at 2500 RPM -- Coaxial Vs. Isolated

3.3.4 Motor 2 Performance Vs. Isolated Motor 2 at 2500 RPM

At 71% of the operational RPM, motor 2 produced 42.826 newtons of thrust as an isolated, single-rotor system. This value is 2.35% greater than motor 1's thrust generation at the same RPM. As previously mentioned, this deviation is likely due to an imperfection in the testing, as both rotors use the same motor and power supply.

Much like the data for 57% of the operational RPM, Table 4 shows that damages to motor 2's thrust generation caused by aerodynamic interactions within the coaxial rotor system are far greater than the effect experienced by motor 1. Motor 2's thrust generation percent differences between the coaxial and isolated rotor systems span from 19.551% to 29.023% over the range of separation distances tested, with the largest differential (i.e., 10.854 newtons) occurring at the 90% mark. Even the smallest percent difference for motor 2 greatly outweighs the largest distance for motor 1 at the same RPM, further supporting the idea of "dirty" airflow being passed to the lower rotor from the top rotor. Since the impairment of motor 2's thrust generation does not fully dissipate over the tested blade separation distances, it appears that separation distances of up to 100% of the blade diameter are not significant enough to see a full removal of aerodynamic interference. However, the 10% mark again represents one of the lowest percent differences for motor 2, so the idea of the turbulent flow from motor 1 taking a certain distance to disperse fully and become sporadic is still viable. With the overall performance of motor 2 comparing far less favorably to its isolated results than motor 1, it does support the previously noted trend of the thrust performances of the motors being inversely related.

At 71% of the operational RPM, motor 2 generated a magnitude of 1.301 newton meters of torque when operated as an isolated, single-rotor system. Table 4 shows that over the tested separation distances for the coaxial rotor system, the percent differences in torque generation from the isolated motor 2 value range from 6.269% to 11.892%. The greatest percent difference occurs at a separation distance of 10%, and the smallest difference occurs at the 40% mark.

Much like the results seen at 57% of the operational RPM, motor 2's torque generation levels for the coaxial system seem to synchronize with the torque levels generated by motor 1 at the same RPM. This reduction in motor 2's torque performance allows the torque generated by the two motors to cancel out in the overall coaxial rotor system, which again suggests that the lower rotor's torque performance is degraded by interaction with the upper rotor. In addition, the consistently large deviations in torque percent difference over the tested separation range demonstrate that motor 2's torque levels are not capable of recovering to their isolated performance level when operating within the coaxial system at separation distances of up to 100% of the blade diameter.

Motor 2 Thrust and Torque Generation at 2500 RPM Based on Blade Diameter Percentages				
Separation Distance	**Thrust (Newtons)**	**Thrust Percentage Difference (%)**	**Torque (Newton Meters)**	**Torque Percentage Difference (%)**
10 %	35.187	-19.583	-1.465	11.892
20 %	33.293	-25.047	-1.421	8.789
30 %	33.242	-25.199	-1.414	8.331
40 %	35.199	-19.551	-1.385	6.269
50 %	32.921	-26.154	-1.409	7.985
60 %	33.107	-25.598	-1.448	10.667
70 %	32.636	-27.007	-1.456	11.258
80 %	32.475	-27.492	-1.440	10.149
90 %	31.972	-29.023	-1.423	8.978
100 %	32.302	-28.016	-1.428	9.307
Isolated	42.826	0.00	-1.301	0.00

Table 4. Motor 2 Thrust and Torque Generation at 2500 RPM -- Coaxial Vs. Isolated

3.3.5 Motor 1 Performance Vs. Isolated Motor 1 at 3000 RPM

At 86% of the operational RPM, motor 1 generated 60.004 newtons of thrust when operated as an isolated, single-rotor system. Unlike the previously discussed RPMs, Table 5 confirms that, for 86% of the operational RPM, at no blade separation distance did motor 1 outperform its isolated thrust production, hence why all percentage differences are negative. As shown in Figure 12, only slight increases and decreases were present in the motor 1 thrust production data, and this trend is also visible in the percent difference shown in Table 5. Over the range of tested separation distances for the coaxial rotor system, the smallest differential is 0.336% at 80% blade separation, and the largest differential is 6.594%, occurring at the 100% mark. The 80% region's small percent difference likely represents the shifted and magnitude-reduced optimized performance hump seen in motor 1's thrust data at 71% of the operational RPM. There are regions where the percent difference for the coaxial and isolated systems for motor 1 were within 2% (i.e., 60%, 70%, 80%, 90%). While these distances are consecutive, the magnitude of the percent differences are not consistently dropping, and there is a large spike at the 100% mark, which points to there not being a significant relationship between reductions in aerodynamic interference and increases in separation distances of up to 100% of the blade diameter.

At 86% of the operational RPM, motor 1 produced 2.128 newton meters of torque when ran as an isolated system. As with the previously analyzed RPMs, Table 5 shows that the percent differences for the torque generation of motor 1 are extremely small. Six of the ten tested distances record percent differences of less than 1.5% (i.e., 10%, 20%, 30%, 40%, 50%, and 80%). The largest percent difference from the levels generated by the coaxial system compared to the isolated system for motor 1 is a mere 2.248% (i.e., .048 newton meters). However, it occurs at a separation distance of 100%. This data suggests that the torque generation of motor 1 at 86% of the operational RPM is not a significant function of aerodynamic interference due to variations in blade separation distance of up to 100% of the blade diameter.

Motor 1 Thrust and Torque Generation at 3000 RPM Based on Blade Diameter Percentages				
Separation Distance	**Thrust (Newtons)**	**Thrust Percentage Difference (%)**	**Torque (Newton Meters)**	**Torque Percentage Difference (%)**
10 %	57.191	-4.801	2.150	1.047
20 %	58.777	-2.066	2.120	-0.353
30 %	58.288	-2.902	2.117	-0.490
40 %	58.438	-2.645	2.117	-0.495
50 %	58.331	-2.828	2.130	0.127
60 %	59.039	-1.621	2.093	-1.625
70 %	59.271	-1.228	2.086	-1.951
80 %	59.803	-0.336	2.110	-0.823
90 %	59.036	-1.626	2.088	-1.898
100 %	56.174	-6.594	2.080	-2.248
Isolated	60.004	0.00	2.128	0.00

Table 5. Motor 1 Thrust and Torque Generation at 3000 RPM -- Coaxial Vs. Isolated

3.3.6 Motor 2 Performance Vs. Isolated Motor 2 at 3000 RPM

At 86% of the operational RPM, motor 2 generated 62.186 newtons of thrust when operated as an isolated, single-rotor system. This value is 3.57% higher than the thrust generated by the isolated motor 1 with the same setup parameters and RPM, likely due to imperfections in the data acquisition process.

As with the previously tested RPMs, Table 6 demonstrates that motor 2 experiences far more degraded thrust performance than motor 1 due to the coaxial system interactions, which is highlighted when each is compared to their respective isolated system results. The thrust production percent difference of motor 2 at the tested separation distances ranges from 20.942% to 29.694%. The smallest differential occurred at a separation distance of 10%, and the greatest differential occurred at a separation distance of 90%. The smallest percent difference for motor 2 is over 16% greater than the largest percent difference for motor 1. This discrepancy in performance between motors, and the 10% mark representing the lowest percent difference for motor 2, again supports the explanation of “dirty” flow between the upper and lower rotors. While motor 2’s thrust production does begin to return to its isolated value as the blade separation distance increases, it does not manage to reach the isolated level. This data further supports the conclusion that a separation distance of 100% of the blade diameter is insufficient to remove the aerodynamic interference experienced by the lower rotor of a coaxial system.

At 86% of the operational RPM, motor 2 generated a magnitude of 1.896 newtons meters of torque when tested as an isolated, single-rotor system. Table 6 shows that the percent difference in torque generation for motor 2 over the tested blade separation distances ranges from 4.838% to 12.552%. The smallest percent difference occurs at a blade separation of 100%, while the largest percent difference occurs at a blade separation of 10%.

At 86% of the operational RPM, the torque generation from motor 2 again synchronizes with the torque generation from motor 1 over the tested blade separation distances, which validates the claim that the torque generated by the overall coaxial system would effectively cancel out at the tested RPM. However, the significant percent differences between motor 2's coaxial system data and isolated data suggest that the lower rotor of the coaxial system experiences reduced performance due to interactions with the dirty wake of the upper rotor when operating at 86% of the operational RPM. This reduction in performance inhibits motor 2 from matching its isolated torque production levels for at least a separation distance equivalent to the blade diameter.

Motor 2 Thrust and Torque Generation at 3000 RPM Based on Blade Diameter Percentages				
Separation Distance	**Thrust (Newtons)**	**Thrust Percentage Difference (%)**	**Torque (Newton Meters)**	**Torque Percentage Difference (%)**
10 %	50.397	-20.942	-2.149	12.552
20 %	47.321	-27.149	-2.082	9.357
30 %	47.167	-27.468	-2.075	9.045
40 %	47.475	-26.830	-2.089	9.682
50 %	48.556	-24.616	-2.098	10.139
60 %	47.607	-26.558	-2.115	10.916

70 %	46.993	-27.832	-2.097	10.087
80 %	46.363	-29.154	-2.096	10.035
90 %	46.107	-29.694	-2.091	9.787
100 %	49.698	-22.322	-1.989	4.838
Isolated	62.186	0.00	-1.896	0.00

Table 6. Motor 2 Thrust and Torque Generation at 3000 RPM -- Coaxial Vs. Isolated

3.3.7 Thrust Percent Difference of Rotor Systems at Tested RPMs

The tables displayed above represent the comparison of each motor within the coaxial system to its respective isolated, single-rotor system at one of the three tested RPMs. While these tables are useful to analyze each motor's aerodynamic performance at a particular RPM, a more holistic view is also beneficial. Figure 20 and Figure 21 provide separate comparisons of the thrust generation for motor 1 and motor 2, with respect to RPM, over the tested blade separation distances.

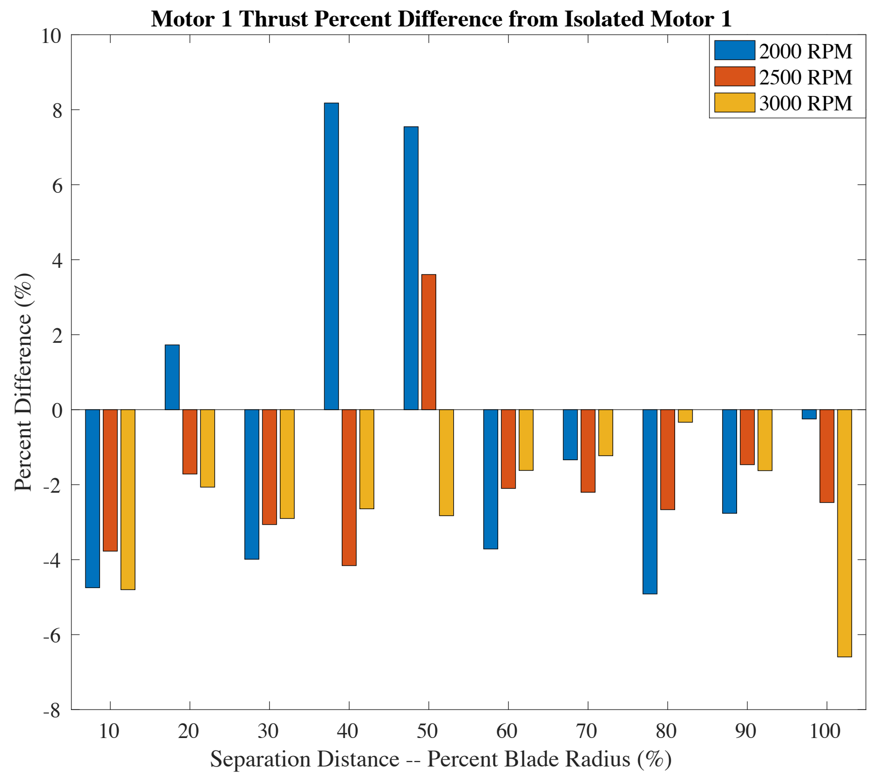

Figure 23. Motor 1 Thrust Percent Difference from Isolated Motor 1

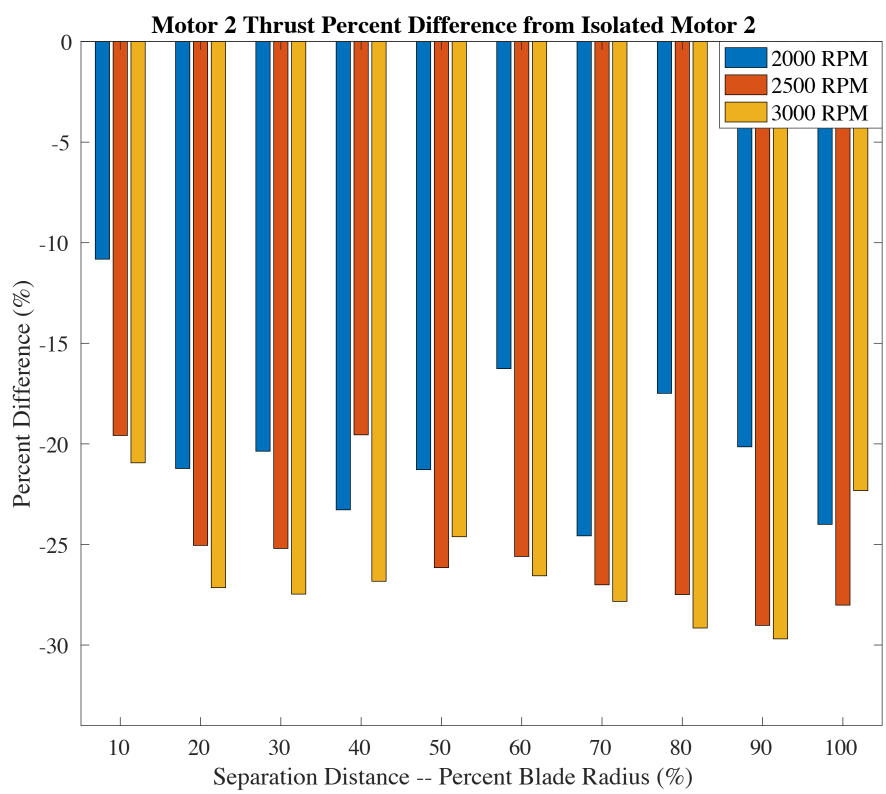

Figure 24. Motor 2 Thrust Percent Difference from Isolated Motor 2

3.3.8 Torque Percent Difference of Rotor Systems at Tested RPMs

As explained above in Section 3.3.8, Figures 22 and 23 provide more holistic views of the percent difference comparisons between each motor in the coaxial rotor system and its respective isolated, single-rotor system. Figure 23 and Figure 24 compare the torque generation percent differences of the systems, with respect to RPM, over the range of tested blade separation distances. A negative percent distance denotes a reduction in torque generation from the respective isolated rotor system.

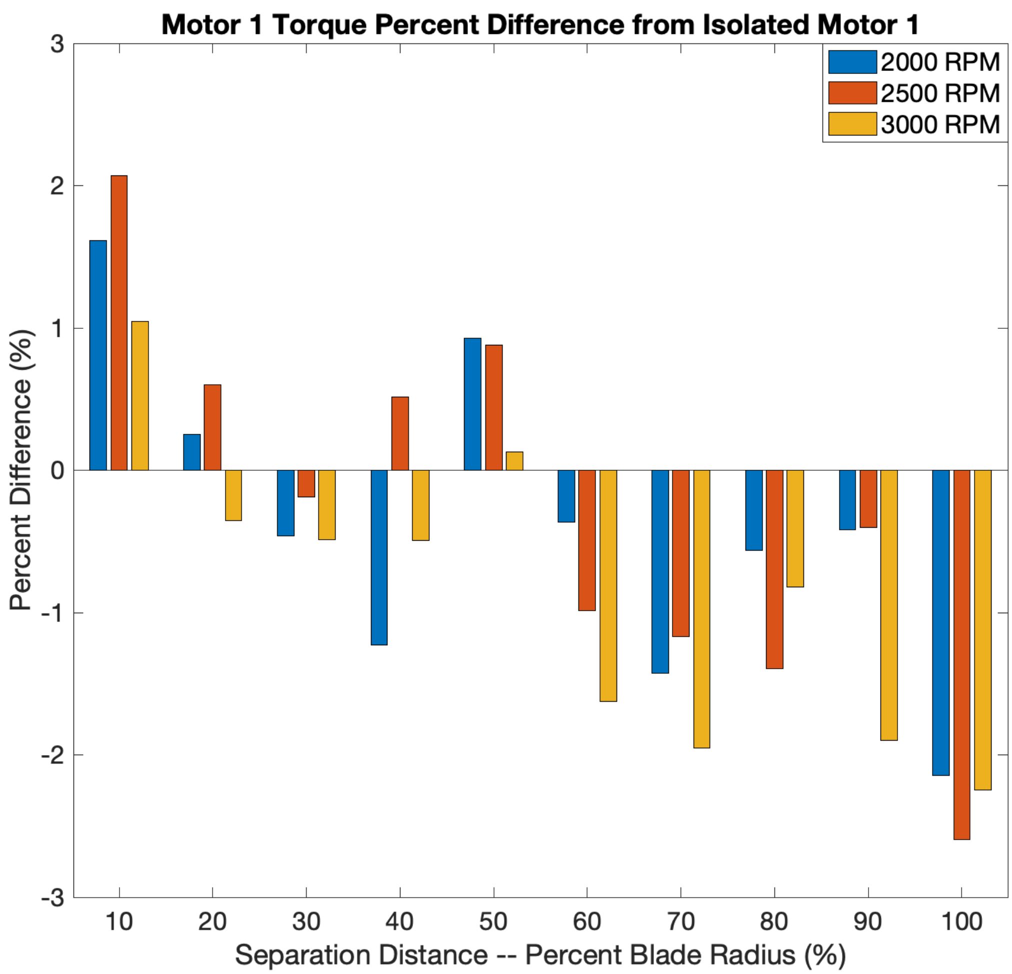

Figure 25. Motor 1 Torque Percent Difference from Isolated Motor 1

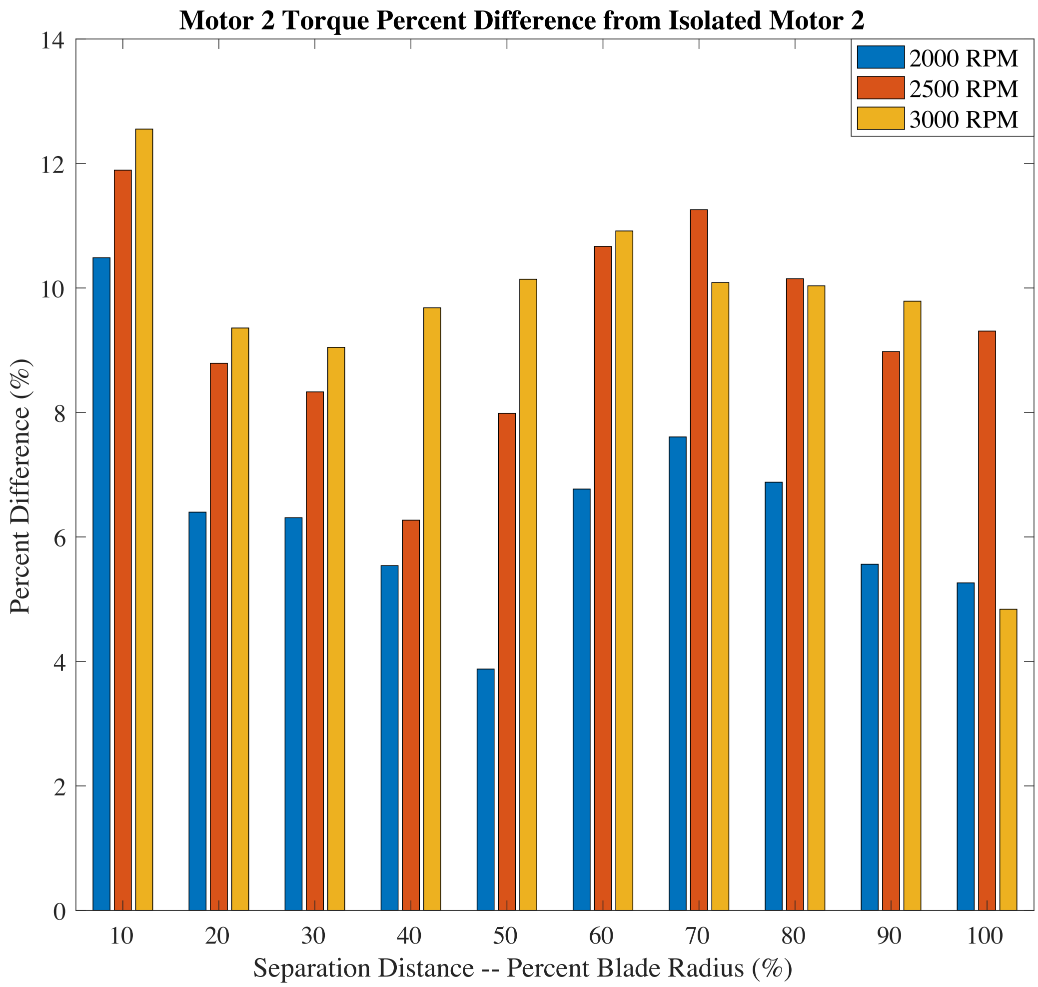

Figure 26. Motor 2 Torque Percent Difference from Isolated Motor 2

3.4 Comparison of Results to Literature

The primary question revolving around a coaxial rotor system is if blade separation distance affects the aerodynamic performance of the overall coaxial rotor system. The initial expectations of experts were that as the blade separation distance changes, the two rotors would experience differing levels of aerodynamic interference, affecting the thrust and torque generation of each individual motor. Previous research has provided mixed results, with separate sources claiming both sides of the spectrum. Upon completing a series of coaxial rotor system tests in 1997, Coleman concluded that altering the blade separation has negligible effects on the aerodynamic performance of the overall coaxial rotor system and alters only what percentage of the overall thrust each individual blade produces [4]. However, research scientist Manikandan Ramasamy also completed comparable tests and determined that there were distinct regions of separation distance where aerodynamic interference between the two rotor blades was prevalent, reducing the overall aerodynamic performance of the system. Ramasamy found that at a certain large separation distance, the aerodynamic interference was no longer present, and the two blades of the coaxial rotor system essentially operated as two isolated, single-rotor systems [2].

Comparing the findings of this research regarding thrust generation with those reached by Coleman and Ramasamy results in an interesting dilemma. While the results of this thesis suggest that blade separation distance affects the thrust generation of the coaxial rotor system, the performance of the rotors did not consistently improve and ultimately reach their isolated performance metrics, as documented by Ramasamy.

Ramasamy found that when axial separation was less than 20% of the untwisted blade diameter, the upper rotor's performance rapidly reduced, and the lower rotor's performance improved. The adverse effect ultimately resulted in an overall decrease in performance. However, the research for this thesis demonstrated the exact opposite relationship for blade separation distances under 20% of the blade diameter and even highlighted a region (i.e., 12.5% to 20%) where motor 1 outperformed its isolated levels at 57% of the operational RPM. In this optimized region, the total aerodynamic performance of the coaxial system improved. Furthermore, Ramasamy found that when axial separation was between 20% and 75% of the untwisted blade diameter, the upper rotor demonstrated a gradual reduction in performance, and the lower rotor demonstrated a gradual increase in performance. The adverse effect ultimately resulted in negligible performance change. The research for this thesis demonstrated a fluctuating, adverse relationship for blade separation distances ranging from 20-75% of the blade diameter, and again highlighted regions (i.e., 35% to 57.5% and 45%-57.5%) where motor 1 outperformed its isolated levels at respective RPMs 57% and 71% of the operational RPM. In this optimized region, the total aerodynamic performance of the coaxial system improved. Finally, when axial separation was greater than 75% of the untwisted blade diameter, Ramasamy found that the aerodynamic performance of the overall coaxial system and each individual rotor was unaffected by changes to the blade separation distance. Although the research for this thesis did not find any regions of optimized performance at blade separation distances greater than 75% of the blade diameter, there were still signs of aerodynamic dependency on the blade separation distance.

It must be noted that the previously discussed performance discrepancies could be due to Ramasamy's use of untwisted, straight blades, while the blades used for this research were twisted. Therefore, the discrepancies might be a result of differing downwash structures, as downwash seems to be a crucial factor regarding the interaction between the rotors of the coaxial system.

The existence of improved total thrust generation for the coaxial rotor system due to regions of optimized motor 1 thrust performance also contradicts Coleman's conclusions that altering blade separation distance alters only what percentage of the overall thrust each individual blade produces. Therefore, the findings of this thesis suggest that the relationship between blade separation distance and aerodynamic performance is much more complex than previously expected but that there are potential opportunities for aerodynamic performance benefits.

Chapter 4. Conclusions and Remarks

4.1 Conclusions

The purpose of the research specific to this thesis was to determine how large percentage separation distances affected the aerodynamic performance (thrust and torque generation) of rigid coaxial blades in hover at three different RPMs. The interaction of the rotors in the coaxial system was analyzed to quantify the presence and effect of aerodynamic interference in the system. Additionally, blade separation distance was varied to determine if said aerodynamic interference was a function of separation distance. Torque levels generated by the coaxial system were inspected to determine if the claims of a coaxial rotor system removing the need for a torque-stability tail system were correct. Finally, the generated results of the coaxial rotor system were quantitively compared to the results of the same motors operated as isolated, single-rotor systems at a controlled power supply.

After processing the recorded data and running it through a low-pass, second-order Butterworth filter, the following conclusions were reached:

With respect to the coaxial rotor system, there was an obvious inverse relationship between the aerodynamic performance of the two rotors. At all three tested RPMs, an improvement in one motor’s thrust generation was characterized by varying levels of performance reduction in the opposite rotor. Typically, this trend was depicted as an improvement in the thrust generation of the upper rotor, accompanied by a larger magnitude reduction in the thrust generation of the lower rotor. This inverse relationship was also distinguishable in the torque data, but the deviations were far smaller in magnitude. Therefore, the completed testing clearly confirmed that the upper rotor of a coaxial rotor system has impairing effects on the aerodynamic performance of the lower rotor. This relationship appears to be a function of aerodynamic interference between the two rotors of the coaxial system. The interference is most likely due to the airflow reaching the lower rotor having already transitioned to turbulent flow, as it is the wake of the upper rotor, which creates a sporadic and "dirty" air supply for the lower rotor. This conclusion is further supported by the lower rotor's closest percent difference to its isolated thrust results occurring at a blade separation distance of 10% (2.7 inches), which would likely not be sufficient space for the wake to separate and become completely sporadic before reaching the lower rotor. Additionally, a blade separation distance of up to 100% of the blade diameter was proven to be insufficient to entirely remove the aerodynamic interference between the rotors of the system at all tested RPMs. Neither the thrust nor torque generations of either motor recovered to their respective, isolated results over the tested range of separation distances.

Perhaps the most significant finding was blade separation regions where motor 1 outperformed its isolated, single-rotor system results for that respective RPM. At 57% of the operational RPM, these optimized motor 1 thrust performances occurred between separation distances of 12.5% - 22.5% and 37.5% - 52.5%, outperforming their isolated level by 3.28% and 10.26%, respectively. At 71% of the operational RPM, the smaller magnitude peak dropped below the isolated system's performance level, and the larger magnitude peak both shifted right and decreased. However, at a blade separation distance of 50%, tests at 71% of the operational RPM still produced a motor 1 thrust generation that outperformed its respective isolated system by 3.61%. At 86% of the operational RPM, there were no longer any regions where the coaxial system's upper rotor outperformed its respective isolated system. Analysis of the standard deviation bar curves for the unfiltered thrust data confirmed the credibility of these optimized motor 1 thrust performance sections, as the peaks were easily visible prior to filtering. This trend suggests that the aerodynamic performance of a coaxial rotor system is dependent on RPM at low rotational speeds but becomes independent of RPM at higher rotational speeds. Additionally, the peaks in total thrust generation by the coaxial rotor system coincided with the peaks in thrust production by motor 1, which suggested that motor 1 was the dominating factor in the coaxial system's overall thrust performance. Therefore, for low RPMs, the regions where motor 1 manages to outperform its respective isolated, single-rotor system in thrust production represent the most efficient blade separation distances for a coaxial rotor system at that respective RPM.

Regarding a potential relationship between aerodynamic performance (thrust and torque generation) a nd blade separation distance, analysis of the coaxial rotor system's performance at the three tested RPMs suggested a relation between thrust generation and blade separation distance aside from the optimized motor 1 sections. Two of the three RPMs demonstrated sinusoidal-like patterns of increasing and decreasing performance for one of the system's rotors, with corresponding adverse performance for the other rotor. The other tested RPM depicted gradual increases and decreases in thrust generation over the tested separation distances.

However, this relationship between blade separation distance and thrust generation was shown not to be a linear line. As blade separation distance increased, thrust generation did not consistently increase, hence the mentioned sinusoidal patterns. Alternatively, it appears that altering the blade separation of the rotors merely changes the orientation of the airflow reaching the lower rotor, which creates the discussed regions of differing performance, with respect to the blade separation. In other words, while blade separation does affect the thrust generation of the coaxial rotor system, the expected result of an increased separation distance being accompanied by an increase in aerodynamic performance was not confirmed for the range of blade separation distances analyzed in this research.

The relationship between separation distance and torque generation by the two motors within the coaxial rotor system was less pronounced than the trends observed with thrust. As the blade separation increased, the torque generated by both motors did demonstrate the previously described adverse relationship but with only small-magnitude deviations. The deviations that did occur fluctuated between increases and decreases in torque generation that were in no way linear to blade separation changes.

Analysis of the individual motors of the coaxial system compared to their respective results as isolated systems provided a few additional performance takeaways. The torque generation percent differences between the coaxial and isolated system results for motor 1 were small in magnitude (often less than 5%). However, the torque percent differences did increase to levels of up to 8.17% at the blade separation distances corresponding to the sections of optimized motor 1 thrust performance. These increases in torque generation supported the credibility of the thrust signals for these sections.

The lower rotor's torque generation demonstrated slightly larger deviations from its isolated results (averaging approximately 8%) than the upper rotor, which seemed to allow for the synchronization of the torque generation between the two rotors. In other words, when operated within the coaxial system, the rotors demonstrated torque generations of equal magnitudes in opposing directions. This result confirms the theory that counter-rotating coaxial rotor systems remove the requirement of a torque-stabilizing tail rotor, as the total torque production caused by the rotor system effectively cancels out.

Ultimately, the adverse relationship between the upper and lower rotors of the coaxial rotor system allows the upper motor to outperform its own isolated, single-rotor system results by notable margins at certain blade separation distances with respect to RPM. These regions dissipate as RPM increases, and at high RPMs, the lower motor's performance reduction is no longer great enough to allow the upper rotor to outperform its own isolated results.

Therefore, a coaxial rotor system's ability to elevate the performance of the upper rotor above its respective isolated performance is dependent on the blade separation distance and operation RPM. The employment of a coaxial rotor system is not guaranteed to elevate the performance of either rotor above its respective isolated performance at all blade separation distances and RPMs. The most efficient blade separation distances for a coaxial rotor system operating at 57% and 71% of the operational RPM are 45% and 50% of the blade diameter, respectively. Outside the previously discussed regions of optimized motor 1 thrust production, the coaxial rotor system merely offers a cumulative thrust generation level larger than an isolated single-rotor system while keeping the rotorcraft's overall area footprint constant.

4.1 Suggestions for Future Work

After analysis of the research completed in this thesis, there are some opportunities for future work that would allow for further understanding of the coaxial rotor system's aerodynamic performance.

One approach to validating the theory laid out in this thesis regarding "dirty" wake evolution would be to reduce the blade diameter of the upper rotor while leaving the lower rotor diameter unchanged. The smaller upper rotor should allow the lower rotor to have relatively undisturbed airflow on the section of its blade outside the reach of the upper rotor's blade diameter. The results of this adjustment should be more evident at close separation distances, as the airflow is turbulent but still compact. This differential in blade diameter could then be tested over the same separation distance (2.7” to 27”). Ideally, these tests would result in slightly smaller thrust generations from the upper rotor (due to its reduced blade diameter) and notably larger thrust production by the lower rotor due to a portion of its air inflow being “cleaner.” The goal of the research would be to produce a cumulative thrust larger than the values generated by the coaxial rotor system with equal blade diameters over the same tested separation distances.

Another factor worthy of investigation to better understand the aerodynamic performance of a coaxial rotor system in hover is ground effect. In practical use, a helicopter performing a takeoff/landing or maintaining a low-altitude hover experiences interaction with the ground below. The ground acts as an immovable barrier for wake funneled down from the lower rotor of the coaxial system, which does not allow the air to disperse cleanly from system’s operating region. The tests ran for this thesis did not account for this effect, as the air was unblocked and clear to flow “infinitely” far from the lower rotor. A large steel plate attached at a fixed distance from the lower rotor would simulate the ground, allowing for insight into the interactions between the two rotors of the coaxial rotor system and the ground over the same range of tested separation distances.

Bibliography

1. Barbely, N. L., Komerath, N. M., & Novak, L. A. (2016). A Study of Coaxial Rotor Performance and Flow Field Characteristics. Retrieved November 27, 2022.

2. Ramasamy, M. (2015). Hover Performance Measrements Toward Understanding Aerodynamic Interference in Coaxial, Tandem, and Tilt Rotors. Retrieved November 27, 2022.

3. Bhagwat, M. (2018, September). Co-Rotating and Counter-Rotating Coaxial Rotor Performance. Retrieved November 22, 2022.

4. Coleman, C. P. (1997). A Survey of Theoretical and Experimental Coaxial Rotor Aerodynamic Research. Retrieved November 27, 2022.

5. Fernandes, S. D. (2017). *Performance analysis of coaxial helicopter in hover and forward flight* (thesis).

6. *Kamov Company*. Kamov Company - Russian Defense Industry. (2000, August 24). Retrieved November 27, 2022, from https://nuke.fas.org/guide/russia/industry/kamov.htm

7. Lee, C.-Z. (2017, July 21). *Signals and the Frequency Domain*. Engineering 40M Lecture Notes. Retrieved December 26, 2022, from https://web.stanford.edu/class/archive/engr/engr40m.1178/

8. Linden, A. (1995). *Rotary Wing Legacy*. Sikorsky Archives. Retrieved November 28, 2022, from https://www.sikorskyarchives.com/D_Rotary_Wing_Legacy.php

9. Linden, A. (1995). *Sikorsky Aerial Armored Reconnaissance Vehicle (AARV)*. Igor I Sikorsky Historical Archives. Retrieved November 27, 2022, from https://sikorskyarchives.com/AARV

10. Mathworks. (n.d.). *Butterworth Filter Design*. Help center - MATLAB. Retrieved December 26, 2022, from https://www.mathworks.com/help/signal/ref/butter.html

11. Prasad Rao, J., Holzsager, J. E., Maia, M. M., & Diez, J. F. (2022, August 17). Experimental Study into Optimal Configuration and Operation of Two-Four Rotor Coaxial Systems for eVTOL Vehicles. Retrieved November 27, 2022.

12. Ruddell, A. J., Groth, W., McCutcheon, R., & United Technologies Corp Stratford Ct Sikorsky Aircraft Div. (1981, April 1). *Advancing blade concept (ABC) technology demonstrator*. Defense Technical Information Center. Retrieved November 27, 2022, from https://apps.dtic.mil/sti/citations/ADA100181

13. Wicha, J. (2015, July). COAXIAL ROTOR HOVER POWER REDUCTION USING DISSIMILARITY BETWEEN UPPER AND LOWER ROTOR DESIGN. Retrieved November 27, 2022.

14. *X2™ Technology*. Lockheed Martin. (2022, January 25). Retrieved November 27, 2022, from https://www.lockheedmartin.com/en-us/products/x2-helicopter-technology-demonstrator.html

15. Zgoebel, G. (2019, February). AirVectors. Retrieved December 29, 2022, from https://www.airvectors.net

Academic Vita of Aden Scott Funkouser

(304) 703-8860 | asf5357@psu.edu | www.linkedin.com/in/aden-funkhouser

Permanent Address:
1968 Brants Teets Road,
Baker, WV 26801

EDUCATION

Bachelor of Science, Aerospace Engineering — University Park, PA
The Pennsylvania State University — August 2016 – May 2023
Schreyer Honors College
Expected Graduation: May 2023

WORK EXPERIENCE

Manufacturing Employee — Baker, WV
RF Manufacturing Corporation (Private Government Contracting) — August 2016 – August 2021

- Assisted in the construction of surface-to-air missile launchers (Smokey Sam) designed for military testing situations
- Assisted in the refurbishment of control panel circuitry in E-3 Hawkeye surveillance planes
- Assisted in the construction of mobile satellite communication technology for U.S. military personnel
- Soldered hardware onto circuit boards of numerous design specifications
- Performed in-depth inspections of all electronic circuitry and components to ensure quality and functionality
- Used analytical/quantitative skills to adapt government-issue prototypes and technical drawings

Aerospace Engineering Intern — Warrenton, VA
SPARC Research — May 2022 – July 2022

- Used Python to design a Ramjet Cost Estimation GUI that accepted component selections and dimensions from the user and then generated graphical schematics and estimations for non-recurring and recurring costs per engine, tooling costs, material costs, and manufacturing costs
- Translated Fortran 77 programs used for combustion and trajectory analysis (i.e., Aerotherm Chemical Equilibrium, Charring Material Ablation, ZTRAJ) to MATLAB, allowing for more efficient and advanced computational analysis

LEADERSHIP

Vice-President of Sigma Gamma Tau National Aerospace Honor Society — University Park, PA
Penn State Chapter of Sigma Gamma Tau — May 2022 - Present

- Elected Vice-President by peers and alumni for the 2022 – 2023 academic year
- Organized and led tutoring sessions for third-year aerospace engineering students

AEROSPACE ENGINEERING PROJECTS

Programming: — University Park, PA
MATLAB | Simulink | C++ — August 2021 – December 2022

- Used C++ to create a program capable of calculating the classical orbital elements and then transferring them between the ECI and perifocal coordinate systems
- Worked with a team to create a MATLAB code capable of solving a 1D parabolic PDE governing unsteady heat transfer, which would be used in the design of a hypersonic vehicle's cooling system
- Used MATLAB and Simulink to perform design analysis on the control and stability of an aircraft

Design Manufacturing: — University Park, PA
Penn State Sailplane Course | Human-Powered Airplane Fabrication | Propeller Team — August 2021 – Present

- Used provided airfoil (PSU 94-097) data to create a 3-D model of the propeller in SolidWorks
- Built carbon fiber tubes to serve as spars for the propeller system via the employment of wet-layup techniques
- Used a wooden "jig" system to create foam sections with the proper twist specifications, then assembled and vacuum-bagged the sections on the spar to construct propeller

Research: — University Park, PA
Counter-Rotating Coaxial Rotor Systems — August 2021 – Present

- Investigated how thrust and torque generation relates to the separation distance of the rigid rotor blades in a coaxial rotor system
- Determined how the aerodynamic interference experienced by the rotors in a coaxial system affects the aerodynamic performance of each rotor by comparing the coaxial system's performance values to those recorded when each rotor acted as an isolated, single-rotor system

SKILLS

Python Programming | C++ Programing | Fortran Programming | MATLAB | Simulink |Aircraft Design Analysis | Word, Excel, and PowerPoint | SolidWorks | Project Management |Problem Solving | Critical Thinking | Public Speaking

ACTIVITIES

Sigma Gamma Tau Aerospace Honor Society (Vice-President) | Tau Beta Pi National Engineering Honor Society | Vertical Flight Society (VFS)