

**EFFECTS OF AERO-PROPULSIVE INTERACTIONS FOR VARIOUS WING  
INTEGRATION TECHNIQUES ON ELECTRIC DUCTED FAN PERFORMANCE**

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# **EFFECTS OF AERO-PROPULSIVE INTERACTIONS FOR VARIOUS WING INTEGRATION TECHNIQUES ON ELECTRIC DUCTED FAN PERFORMANCE**

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## SUMMARY

This study explores the aero-propulsive coupling effects of wing blended electric ducted fans (EDF) lifting systems over the EDF unit. Wing blended EDFs and isolated EDF are on the rise as a solution to increase efficiency on regional mobility platforms. Electrification of platforms has permitted the introduction of novel integration concepts that use phenomena like BLI to enhance their performance. The lack of complex mechanical links permits designers to place propulsive devices practically anywhere on the aircraft, opening opportunities for research and development. As noted in the literature review section, little attention has been given to understanding the effects of novel integrations on the EDF. This experimental study aims to examine two edge cases: the leading edge integration and the trailing edge integration. The leading edge integration studied in this work is characterized by having the leading edge of the inlet of the EDF and the leading edge of the wing flushed. The trailing edge features the EDF mounted with the exhaust of the duct flushed with the wing's trailing edge; the angle between the freestream and the EDF is parallel. The duct is translated vertically so that the inlet of the trailing edge EDF is tangent with the wing's surface. Note that this is not an optimization study; simplified integrations that represent the generalized qualities of each integration were adopted. What is novel about the research is that the EDF forces are decoupled from the system loads, providing unprecedented insight into each integration's effects on the EDF itself.

The study was formed by three major test rigs described in the methodology section. The first rig was designed to test EDFs in isolation at various angles of attack. In this test, various sizes of EDFs were tested with a common duct geometry; the sizes ranged from 51  $cm^2$  fan-swept area to 215  $cm^2$  fan-swept area. The EDFs were tested between the cruise condition, edgewise flight, and descent stages; performance data and 6 forces and moments are explored in the results section. The second rig focused on studying the integration of the EDF in both cases, but by introducing a symmetric airfoil design, the upper surface

and lower surface integration was studied. This rig permitted to study such configuration in the low-turbulence tunnel at lower airspeeds and mostly the cruise condition. For these tests, a Clark-Y duct shape coupled with Schubeler Technologies DS51-HST formed the EDF system. These tests provided insight into all 4 possible integration edge cases and presented interesting findings on pitching moment, thrust output, and performance effects that the integration had on the EDF. The last test rig focused on studying the EDF integration in a more realistic platform (slimmer airfoil) and studying the transition cases, cruise flight, wing stall scenario, and high angles of attack. This test rig was placed in the Low Turbulence Wind Tunnel and the Harper Wind Tunnel. The tests in the low turbulence tunnel focused on edgewise flight, early transition, and the descent cases, studying airspeeds between 2 m/s and 10 m/s. The tests on the Harper Wind Tunnel study the integration in cruise and wing stall conditions at airspeeds between 10 m/s and 20 m/s. In that test, the performance, thrust output, and normal force generated by the duct are investigated.

# **CHAPTER 1**

## **INTRODUCTION AND BACKGROUND**

### **1.1 Motivation**

Regional and urban transportation methods have seen a surge in usage due to the increase in population in urban areas and their surroundings. This has sparked a revolution in how city planners design mobility platforms for current planners; with land routes already saturated and inefficient, the next option is to travel by air. For years, the world has constructed a massive network of air routes that connect continents in short periods, but the world is still landlocked for these periods. For comparison, it takes 1.5 hours to travel from London to Munich by airplane, but for the average Londoner, it takes 1.3 hours to get from home to work. Cutting down travel time is one criterion for the push, but the pollution and expensive operation costs that the air routes produce have slowed its adoption. The EEA reported that an airplane produces 6.7 times more CO<sub>2</sub> per passenger per kilometer traveled than a small car [1]. Due to this, the IATA approved the resolution to achieve Net-Zero emissions by 2050 during its 2021 General Meeting, quoting that the introduction of new technologies in advanced aircraft configurations and propulsive systems will lead to 13% of this effort. It was also projected that by 2030, small aircraft for regional (200 km) routes will feature hybrid-electric or fully electric architectures [2].

Wing integrated Electric Ducted Fans (EDF) have been on the rise as an enabling propulsive technology to help advanced concepts meet the ambitious goals set by the aviation industry. The lack of mechanical transmissions permits these propulsion devices to be integrated into different sections of the wings or fuselage. These new integration methods allow novel concepts to take advantage of aero-propulsive coupling effects that could help increase the efficiency of the overall vehicle.

## 1.2 Literature Review

The topic of boundary layer ingesting propulsion systems has been studied extensively to reduce fuel burn on subsonic and transonic flights. These studies were done on legacy and novel blended-wing body airframes alike. Uranga et. Al. showed a power reduction required of 6% when using Boundary Layer Ingestion (BLI) propulsive mounted on the fuselage of similar size to an A320 jetliner. In the study Uranga et. Al. positioned the thrusters in various fuselage locations and found that placing them in locations where the momentum deficit is the largest [3]. Hartuc performed a comprehensive theoretical and experimental analysis of propellers positioned in the wake behind the trailing edge of a fuselage and found an 18% reduction in shaft power required to drive the propeller [4]. The finding supports the claim by Uranga et al. that positioning the propulsive device in a momentum deficit zone can increase performance.

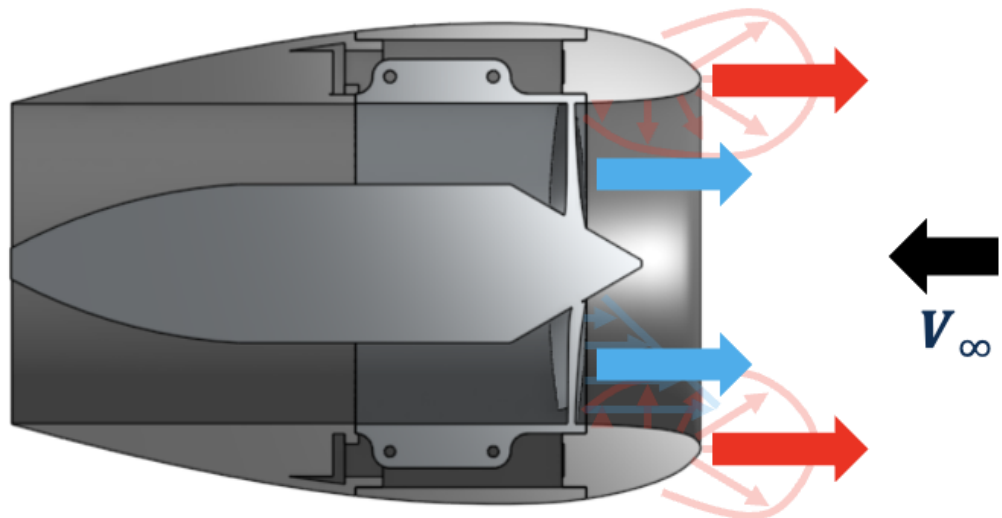
Perry et. Al studied the aero-propulsive effects of a trailing edge-mounted EDF array on a small subsonic aircraft (SR22 wing)[5]. Perry et al. showed that adding the propulsor array increases the circulation over the wing, effectively coupling the wing's lift curve slope with the propulsor's thrust. In addition to the positive effects, the introduction of the EDF array induced rolling and pitching moments that would affect the vehicle handling and the changes in glide performance due to the windmilling of the EDF in the event of a power-loss scenario [5].

Most of the previous work on BLI propulsion mechanisms has focused on studying the integration for large high-speed transport aircraft or has only focused on the effect of the integration at a system level for smaller aircraft. Decoupling of the EDF forces for various wing integrations has been given little attention. The rise of novel configurations like the Lilium Jet and the Whisper Jet, enabled by electric propulsion, have opened a field of possibilities for enhanced performance. Understanding how the physics changes when integrating the propulsor will drive novel designs, as these could render current architec-

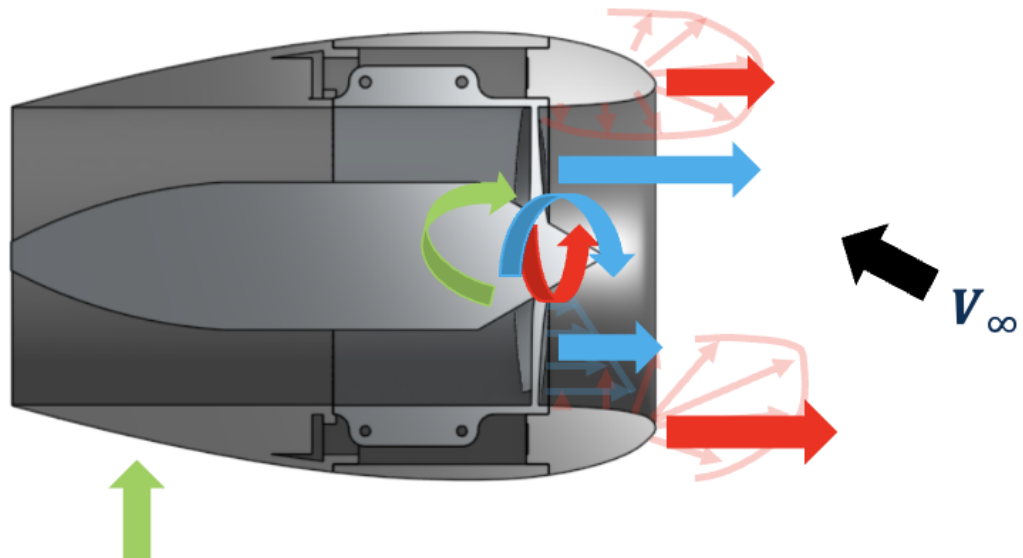
tures inoperable. Kim [6] performed a study on past blended propulsion-wing concepts and concluded that to attain the most benefits and least drawbacks from these installations, it will be important to integrate the propulsion concepts in the early design stages. De Vries et al. [7] presented a framework that considers the aero-propulsive interaction effects of novel ducted fan integration in the early design stage. Experimental results on various configurations could help feed the models for enhanced optimization and design.

### 1.3 Overview of Electric Ducted Fan Aerodynamics

The forces and moments described in this thesis are from the propulsion unit as a whole: a combination of the rotor forces and the duct forces. FIGURE shows a simplified diagram of the dominant forces and moments in the EDF system. The rotor related forces and moments are shown in red. The duct's inlet related forces are shown in blue, and the duct's exhaust related forces are shown in green. Note that a stabilizing moment is defined as one that would pitch the EDF into the flow direction. Figure 1.1(a) shows the forces produced in the cruise condition. Due to the suction effect that the rotor induced velocity has, the duct also produces a streamwise force. As the system is symmetric, both inlet sides produce balancing forces, resulting in a net zero-moment system. The case of a pitched up (positive angle of attack) EDF is shown in Figure 1.1(b). At an angle of attack, the system is not symmetric anymore, hence producing both stabilizing and destabilizing moments. The windward side of the duct is defined as the side facing the wind. The flow is accelerated on the windward inlet lip, creating an enhanced duct force. The acceleration of the flow on the windward lip of the duct reduces the effective angle of attack of the windward side of the rotor plane, causing a thrust reduction. The two force imbalances have competing effects: the duct destabilizes, and the rotor stabilizes. The exhaust forces provide a stabilizing effect on the system. Whether the net moment is stabilizing or destabilizing is a function of the rotor size and duct geometry.



(a) EDF at 0 degrees angle of attack



(b) EDF at positive angle of attack



Figure 1.1: EDF simplified aerodynamic diagram

## **CHAPTER 2**

### **TEST DESIGN AND INSTRUMENTATION**

In this chapter, the various techniques used to complete the thesis are discussed. The first section discusses the development and testing of the measurement equipment used. The discussion includes the development of a low noise amplifier, setting analysis for the Lab-jack DAQ systems, and error quantification of the Interface 6A40A and 6ADF80B loadcells used during testing. The section will then transition to a discussion on the development of the experimental rigs in all three testing conditions: isolated EDF, low-turbulence wind tunnel EDF rig, and Harper wind tunnel EDF rig. This section also discusses the various techniques needed to build the wing sections to create a 2D wing around the EDF integration area. The section covers a description of the test matrix followed for the described experiments.

#### **2.1 Load Measuring Devices**

6 Degree of freedom (6-DOF) force-torque sensors were used during this work. The added information from these devices permits a more in-depth analysis by being able to couple forces with moments and more easily identify the effects of phenomenons like inlet lip stall. Interface force-torque sensors were selected due to their sensing ranges being closer to the expected loads from the EDF. The two chosen devices were the Interface 6A40A and 6ADF80B. The 6A40A force-torque sensor was used for the smaller studied EDFs (DS51 and DS82), while the 6ADF80B was used for the larger EDFs (DS130 and DS215). The 6ADF80B was selected due to its low force sensing range and high moment tolerance. The Interface force-torque sensor ranges are shown on Figure 2.1.

The higher loading on the wing integration tests required a larger capacity loadcell. The ATI Mini58 with its corresponding IFPS boxes (calibrated to the 5V sensing range) was



| Equipment | Interface 6A40A |
|-----------|-----------------|
| Fx (N)    | 200             |
| Fy (N)    | 200             |
| Fz (N)    | 500             |
| Mx (N-m)  | 5               |
| My (N-m)  | 5               |
| Mz (N-m)  | 10              |

(a) Interface 6A40A sensing ranges

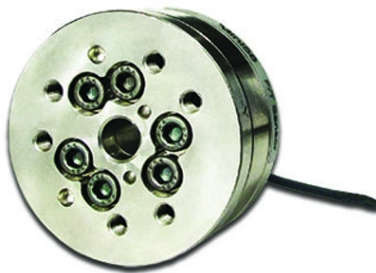


| Equipment | Interface 6ADF80B |
|-----------|-------------------|
| Fx (N)    | 300               |
| Fy (N)    | 300               |
| Fz (N)    | 600               |
| Mx (N-m)  | 30                |
| My (N-m)  | 30                |
| Mz (N-m)  | 30                |

(b) Interface 6ADF80B sensing ranges

Figure 2.1: Interface force-torque sensor sensing ranges

used. That equipment had been validated by other lab members using them under similar circumstances, making the integration of such a device low-risk. The sensing ranges of the ATI Mini58 is shown on Figure 2.2.



| Equipment | Interface 6ADF80B |
|-----------|-------------------|
| Fx (N)    | 700               |
| Fy (N)    | 700               |
| Fz (N)    | 1700              |
| Mx (N-m)  | 30                |
| My (N-m)  | 30                |
| Mz (N-m)  | 30                |

Figure 2.2: ATI Mini58 force-torque sensor sensing ranges



## **2.2 Development and Testing of Measuring Equipment**

### **2.2.1 Data Collection Hardware**

The data collection hardware used for these tests was a suite of LabJack DAQ cards. LabJack is a company that makes products designed for easy data acquisition and control. The common characteristics among all LabJack devices are the multiple multi-function input and output ports equipped with screw terminals to make it easy to connect wires and external devices. The devices also provide several communication channels that enable different data rates and quality levels. The author had conversations with the LabJack engineers to ensure that the products were being used at its full potential. These conversations drove the decision on the language and communication protocol, ultimately leading to the development of the software through Python and communicating via ethernet with the devices.

The flagship LabJack T8 was selected as the primary load data acquisition device due to its ability to perform simultaneous readings across eight analog channels. This would ensure that the author could capture moments in time and not several averaged through time. This capability also permits us to perform unsteady measurements in the future. In some cases, the Labjack T7-Pro was used due to hardware failure on the T8. The LabJack T7-Pro was selected for sensor data collection as the lag between measurements was acceptable to measure DC power and other ambient conditions. Additional LabJack T4 were purchased to control the test, with one of the devices controlling the turn table and the other acting as a PID controller for the motor. The configuration and usage of each device is shown on Figure 2.4.

The pressure data collection was done through an independent system triggered by the LabJack data collection device every time data was taken. Both systems were sampled at a frequency of 1000Hz to ensure reduced cross-talk between channels and reduced clock drift on the pressure scanner. The pressure scanner used for this test was a 64 Channel 10kPa dynamic pressure scanner manufactured by Surrey Sensors based in the UK.

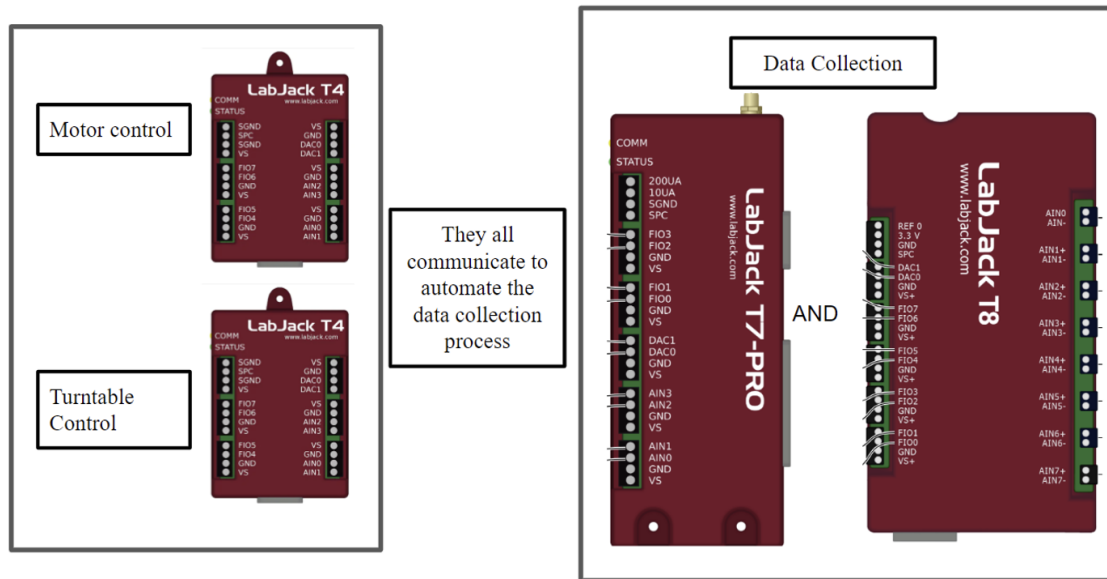


Figure 2.3: Data collection and test control hardware



Figure 2.4: Surrey Sensors 64 channel pressure scanner

### 2.2.2 Development of a low-noise instrument amplifier

Obtaining repeatable, low-noise loads with little post-processing was of primary concern for this testing campaign. To meet these requirements, a low noise loadcell power supply and signal amplifier were developed and tested in-house. The development of the amplifier was motivated by the need to be able to debug the amplifiers without having to go through the manufacturer. The amplifier developed (described in this section) has proven to be a reliable and robust solution and is currently used on all testing campaigns involving an

Interface loadcell.

The development cycle of the amplifier product is shown on Figure 2.5. The initial development of the prototype showed that the primary noise source was the loadcell's power source. The first iteration provided the loadcell with power directly from a precision benchtop power supply, which provided precision up to the millivolt range. This proved too noisy, providing a standard deviation of  $\frac{1}{4}$  of a Newton for a static load; this would magnify in a vibrating load such as the thrust of an EDF. Further development introduced a precision 5V microchip (AD586MNZ) from Analog Devices. The initial prototype proved it was reduced to 0.19N for a static load. To further reduce the noise in the signal, a PCB was designed and manufactured to fit all the necessary electronics. This provided the best results with a standard deviation of measurements of 0.17N using a T7-Pro. During the development process, LabJack released the T8 model featuring simultaneous sampling. The amplifier and the new data collection device yielded the best results at 0.05N standard deviation for 10 seconds of data sampled at 1000Hz.

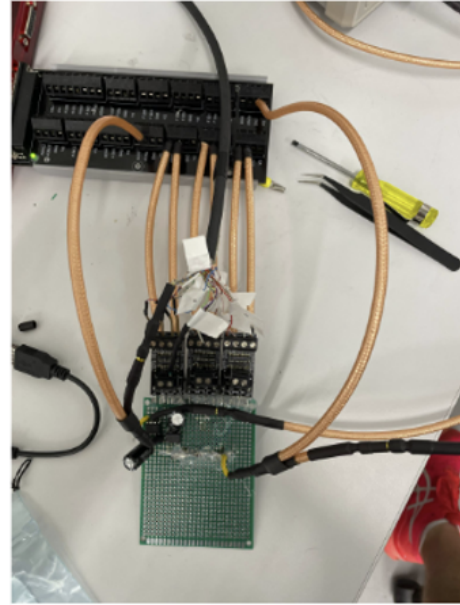
#### *Labjack settings tuning for designed amplifier*

The development of this amplifier also led to a study of the effect that different settings on the LabJack had on the system's performance. It was found that the higher the resolution index of the device (the more bits it sends over from the ADC), the lower the noise and the higher the accuracy of the load measurements. It was identified that for both the T7-Pro and the T8, the index that yielded the best results in terms of accuracy was an index 5 with a sampling rate of 1000 Hz. The complete results from this study are found on Figure 2.6.

It is worth noting that with an index resolution of 1 (worst resolution setting), data can be sampled at 10kHz and still obtain loads within 1% of the expected value, but the noise band increases by 82.67 %. The needs of each experimentalist will determine the selection of these settings. Still, this test shows that coupling the developed amplifier with any Labjack T7 setting makes it possible to obtain repeatable results.



(a) Initial prototype using high precision voltage references and Labjack's amplifier. Sample STD 0.25N (T7-Pro)



(b) Prototype V2, powering the amplifiers with high precision voltage source. Sample STD 0.19N (T7-Pro)



(c) Prototype V3, Manufactured PCB, still using off the shelf amplifier. Sample STD: 0.17N (T7-Pro), 0.05N (T8)

Figure 2.5: Low noise instrument amplifier development cycle

### *Creep Characterization*

The Interface 6ADF80B was characterized for creep and repeatability in-house to ensure the quality of the device and assurance that the team was using the equipment properly.

| Index Study      |                    |          |            |          |         |                      |                      |                                   |                             |
|------------------|--------------------|----------|------------|----------|---------|----------------------|----------------------|-----------------------------------|-----------------------------|
| Resolution Index | Sampling Rate (Hz) | Mean (N) | Median (N) | Mode (N) | STD (N) | mean + (upper bound) | mean - (lower bound) | Range (max reading - min reading) | % error with expected Value |
| 1                | 10,000             | -71.8278 | -71.852    | -71.7748 | 0.53226 | 2.00326              | 1.98934              | 3.9924                            | 0.9272                      |
| 2                | 9,000              | -71.7926 | -71.823    | -71.8044 | 0.41742 | 1.5886               | 1.6848               | 3.2734                            | 0.8778                      |
| 3                | 4,000              | -71.363  | -71.363    | -71.3842 | 0.3248  | 1.4052               | 1.2304               | 2.6436                            | 0.2736                      |
| 4                | 2,000              | -71.3344 | -71.3428   | -71.4262 | 0.2464  | 0.9318               | 0.968                | 1.9                               | 0.2342                      |
| 5                | 1,000              | -71.1686 | -71.1494   | -71.147  | 0.1944  | 0.7788               | 0.8878               | 1.666                             | 0.0476                      |
| 6                | 500                | -71.038  | -71.02     | -71.048  | 0.1646  | 0.623                | 0.56664              | 1.19116                           | 0.1858                      |
| 7                | 250                | -71.004  | -71.0162   | -71.017  | 0.1288  | 0.5204               | 0.5892               | 1.11                              | 0.2298                      |
| 8                | 100                | -70.9566 | -70.9458   | -71.0284 | 0.1254  | 0.4438               | 0.5176               | 0.9738                            | 0.2972                      |

Figure 2.6: Labjack (T7-Pro) resolution index sensitivity study using Interface 6ADF80B and the developed low-noise amplifier at maximum sampling speed

The tests showed that over 1 hour and a load of 71N, the measurement on average crept 0.119% over three tests. A similar characterization was done with the Interface 6A40A, and an average of 0.135% was observed over three tests. The results are within the range specified by the manufacturer. During the testing procedure, tare values are stored every 15 minutes (length on an average test) to ensure that any creep or drift associated with mechanical loosening is considered.

### 2.2.3 Additional Sensors

Independent sensors were selected to measure the other operational conditions, such as the RPM, DC voltage, DC current, and tunnel temperature. AC power was not measured due to the specialized hardware requirement; this does not affect the project's scope. Measuring the difference in DC power still provides insights into overall system power changes. System efficiency identification was outside the scope of this project.

- **RPM Sensor:** To eradicate any aerodynamic effect that an external RPM sensor could generate, the capabilities built into the Electronic Speed Controller (ESC) used during the tests were leveraged. The Castle Creations 160HV and APD controllers had built-in RPM sensors read through the LabJack device.
- **DC Voltage:** To measure DC voltage, a simple voltage divider was constructed and placed close to the ESC to ensure minimal voltage drop between the sensor and the destination of the voltage.

- **DC Current:** This was measured through an inline hall effect current sensor manufactured by Allegro Micro Systems (ACS770). This device comes with different ranges, so two were selected, one with a 400A range and one with a 250A range. These ranges are suitable for all expected current draw ranges.
- **Temperature:** The temperature was measured using a 100K thermistor attached to a voltage divider and powered by the LabJack T7-Pro. The thermistor was set up without any coating to ensure that rapid temperature changes could be captured. The manufacturer specifies that it is accurate to the 0.1 deg system.

## **2.3 Isolated EDF Test Rig Design and Test Matrix**

An initial test was designed to have a baseline and understand the aerodynamic behavior of a stand-alone duct at various angles of attack. The test article closest to the EDF is the conventional turbofan found on subsonic transport aircraft. These have only been studied in low angles of attack and cruise condition. This was because that is their standard operating procedure. As noted in the motivation section, the rise of eVTOL and regional air mobility (RAM) has seen an increase in the use of EDFs as their propulsion unit. The new use case requires the EDF to operate in more unusual attitudes, such as edgewise flight and descent cases. The design of this rig and matrix aimed to get a deep understanding of the aerodynamic and performance effects on the EDF. The EDF was instrumented with pressure taps along various inlet locations, and a wake rake was positioned one duct diameter downstream of the exhaust to achieve this. This, coupled with the 6 DOF and DC power measurements, provided a complete picture of the effects of positioning the EDF at various angles of attack on the aerodynamic and system performance.

### **2.3.1 Electric Ducted Fan (EDF) Tested**

This test campaign aimed to understand the aerodynamic and performance characteristics of EDFs at unusual attitudes, from cruise conditions to descent. Understanding how these

effects changed with scale was also an important goal. The Schuebeler Technologies HST fan line was selected for having the largest selection of sizes and its track record in the aerospace industry. The fans selected ranged from having a fan-swept area of  $51 \text{ cm}^2$  to  $215 \text{ cm}^2$ , the range of their product line. Characteristics of the fans are shown on Table 2.1. This information was obtained directly from the Schuebeler Technologies website.

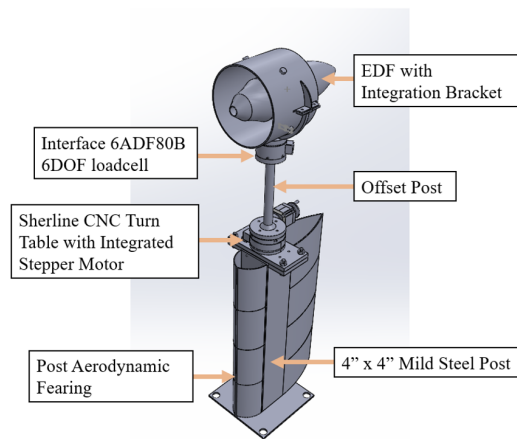
Table 2.1: Tested Schuebeler Technologies HST Fans

|                                                  | <b>DS51-HST</b> | <b>DS82-HST</b> | <b>DS130-HST</b> | <b>DS215-HST</b> |
|--------------------------------------------------|-----------------|-----------------|------------------|------------------|
| <b>Fan Swept Area (<math>\text{cm}^2</math>)</b> | 51              | 82              | 130              | 215              |
| <b>Total Weight (g)</b>                          | 640             | 1240            | 1750             | 3400             |
| <b>Static Thrust Range (N)</b>                   | 53-76           | 71-91           | 135-175          | 215-250          |
| <b>Exhaust Speed (m/s)</b>                       | 93-111          | 87-98           | 92-105           | 84-98            |
| <b>Total Efficiency (%)</b>                      | 71              | 72              | 76               | 78               |

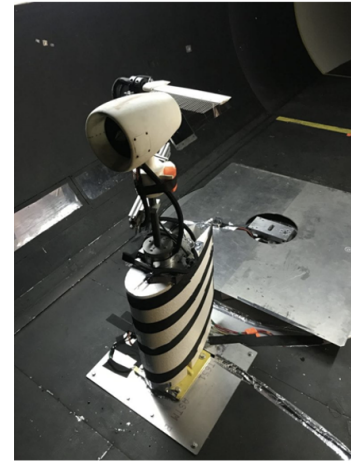
### 2.3.2 Test Stand Design and Manufacturing

The final design for the test stand is shown on Figure 2.7. The stand uses a 4"x 4" with 0.5" wall thickness steel post as the root of the test stand. Due to the thickness of the test section floor, an additional 0.5" aluminum plate was added to the base to ensure minimal flexure of the floor during testing, potentially reducing sources of error. A 1/2" steel plate adapter was welded to the top of the steel post to create a rigid connection between the turn table and the post. To permit the rig to rotate a commercial off-the-shelf (COTS) turn table integrated with a high torque stepper motor. The turn table selected was a Sherline CNC Turn Table; its worm gear construction ensured minimal back drive to the stepper motor, ensuring repeatability and steady movement. Preliminary testing proved that combining the high-torque stepper motor and the worm gear CNC turn table had zero drift and repeatability. A steel offset post was manufactured to obtain maximum separation between the floor attachment and the EDF to the turn table plate, reducing the aerodynamic interactions between the post and the test article. The load cell is then attached to the top of the offset post. A secondary offset post was manufactured to separate the test article from the wake

generated from the loadcell. The offset was maximized to ensure the loadcell is maintained within limits and does not invalidate the calibration matrix.



(a) Isolated test stand CAD



(b) DS82-HST propulsor on test stand inside Harper wind tunnel

Figure 2.7: Isolated test stand design CAD and integration

A loadcell fearing was 3D printed to ensure that the aerodynamic forces measured by the loadcell were only from the test article, reducing the possible measurement error. The fearing design is shown on Figure 2.8. All the manufacturing for the test stand was done internally at Georgia Tech at the Aerospace Engineering Department Machine Shop, and all 3D printing was done at the Aerospace Department Maker Space.

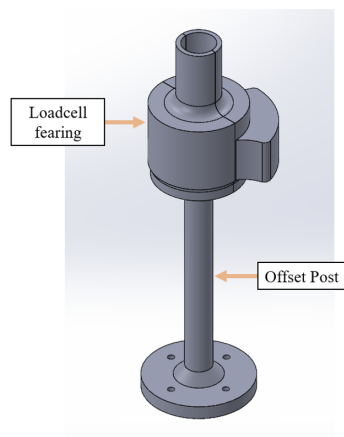


Figure 2.8: EDF loadcell fearing CAD



### 2.3.3 Wind Tunnel Positioning

To ensure the best flow quality, a previous flow survey showed that the best position inside the repaired test section was near the exit of the test section. An integrated platform also drove the decision to position the test article in the location shown on Figure 2.9.

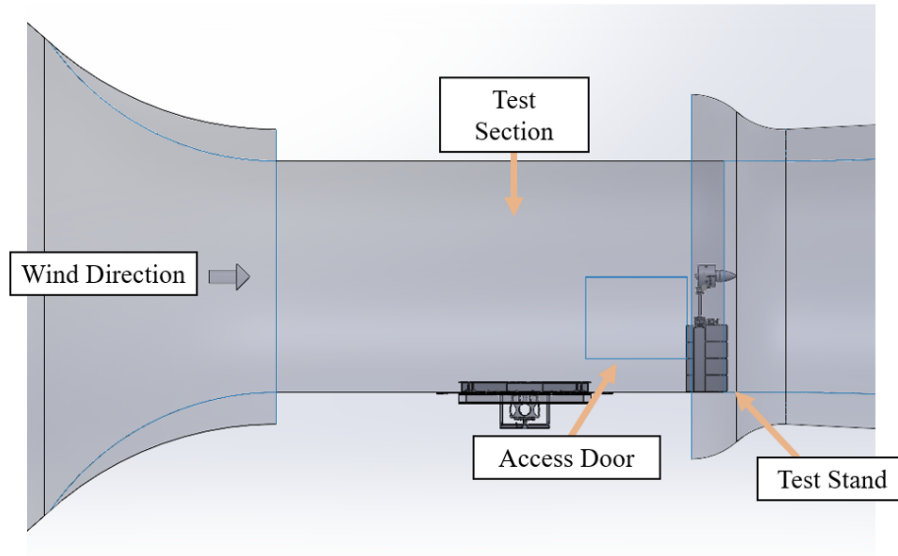


Figure 2.9: Test article positioning in the wind tunnel

### 2.3.4 Axis Definition and Transformations

The loadcell axes are defined in Figure 2.11. The transformed axis to represent the forces and moments seen at the rotor plane are found on Figure 2.12. Equation 2.1 is used to translate the origin and have all the forces and moments at the origin of the rotor-plane. This transformation is vital to capture any aerodynamic effects on the inlet lip of the duct.

$$F_{Transformed} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & z_{offset} & y_{offset} & 1 & 0 & 0 \\ z_{offset} & 0 & x_{offset} & 0 & 1 & 0 \\ -y_{offset} & -x_{offset} & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} \quad (2.1)$$

The offsets applied to each EDF data set are shown on Table 2.2. The physical representation of the offset is shown on Figure 2.10. Note that the fans were not rotated at the rotor plane due to the manufacturer's attachment point constraints. For ease of manufacturing of the test stand, it was preferred that the fan's rotation be done in line with the manufacturer's attachment point.

Table 2.2: EDF origin of rotor plane offset from loadcell origin

| EDF       | X-offset (m) | Y-offset (m) | Z-offset (m) |
|-----------|--------------|--------------|--------------|
| DS51-HST  | -0.042       | 0.0          | 0.133        |
| DS82-HST  | -0.069       | 0.0          | 0.145        |
| DS130-HST | -0.074       | 0.0          | 0.164        |
| DS215-HST | -0.110       | 0.0          | 0.118        |

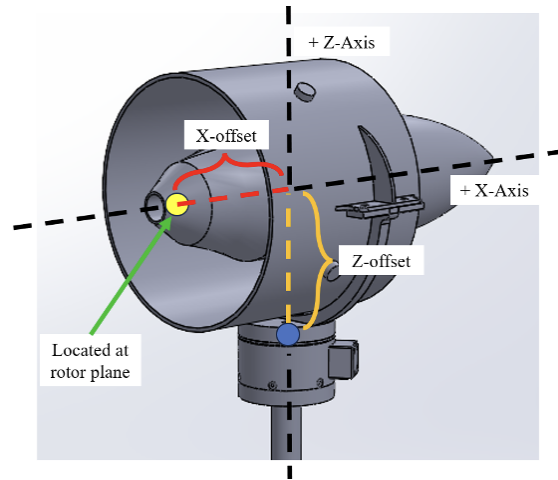


Figure 2.10: Offset physical interpretation

The axis of rotation and how it all aligns with the freestream velocity is shown on

Figure 2.13. Note that the loadcell rotates with the thruster hence the thrust will always be aligned with the  $-F_x$  axis of the loadcell.

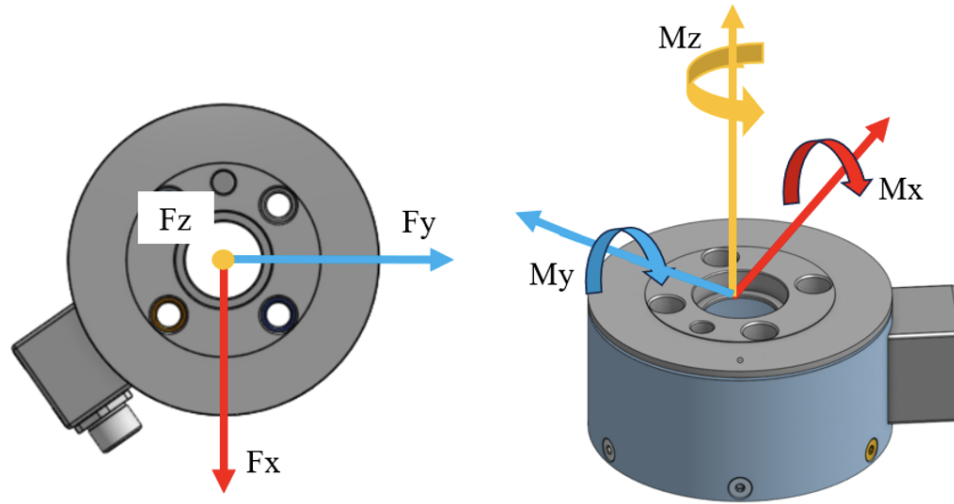


Figure 2.11: Interface loadcell axis definition

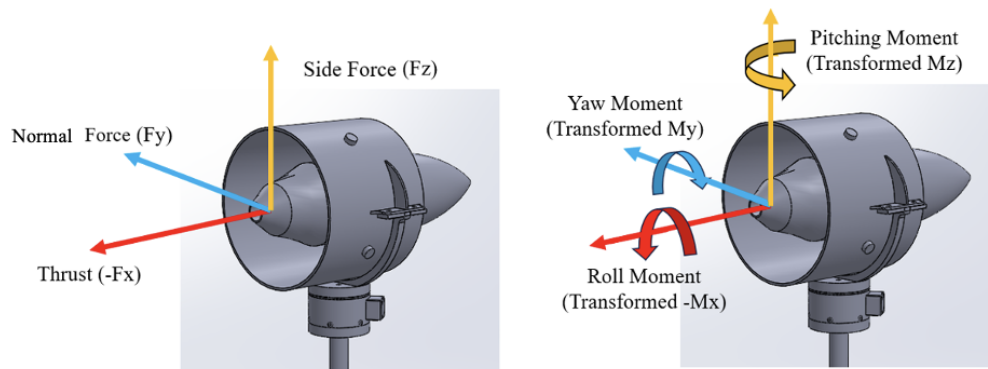


Figure 2.12: Transformed axis definition with origin of the rotor-plane as the origin

### 2.3.5 Tested Duct Geometry and Pressure Port Location

#### *Duct Geometries*

The duct geometry for the Schuebeler HST fans was provided by the project sponsor, Whisper Aero. All the mechanical design for integration on the wind tunnel test was done in-house. The location and design of the inlet pressure ports was done in-house ensuring

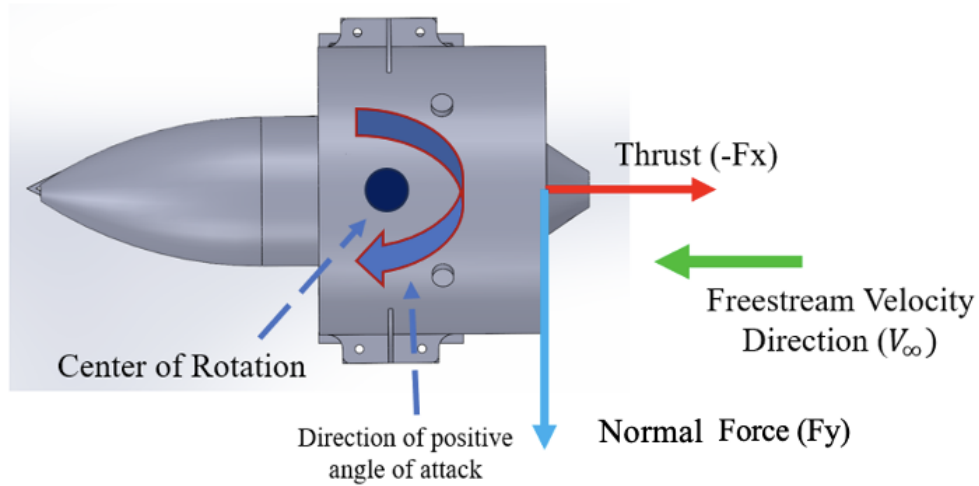
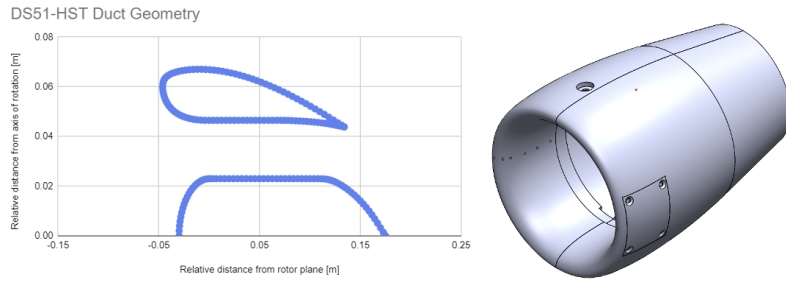


Figure 2.13: Direction of EDF rotation during testing with relation to freestream velocity

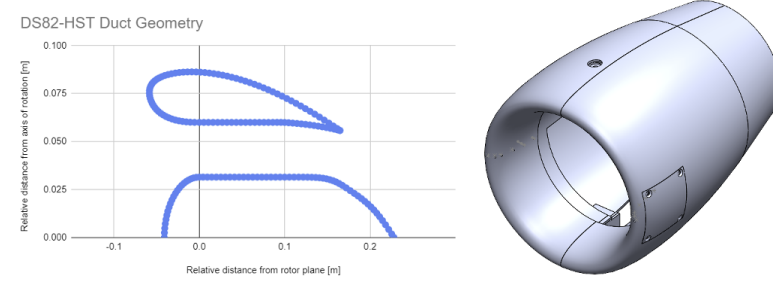
increased number of ports near the leading edge, the number of ports was limited by the space available inside the duct. The mechanical design and manufacturing of all the COTS ducts was done in house using the Mechanical Engineering Department's SLS 3D printer (EOS Formiga P110 (SLS)). The only duct that was outsourced for manufacturing was the DS215 duct and was awarded to Hubs 3D. The geometry and 3D design of the ducts is presented in Figure 2.14.

#### *Pressure Port Locations*

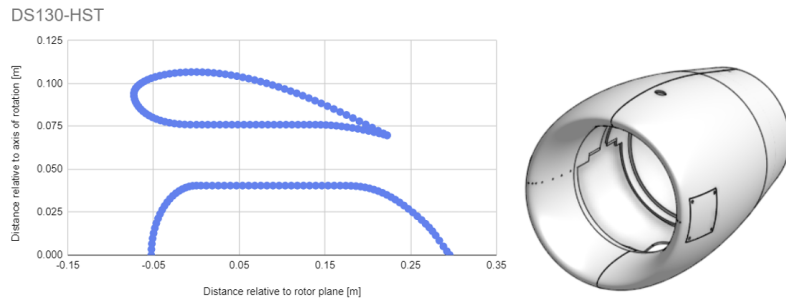
Low frequency pressure ports were positioned along the inlet to provide insight on the nature of inlet distortion and identify separation behaviors for different inlet locations. The set of ports were located on a straight line from the leading edge to the rotor plane, each pressure port line was implemented on the windward side, leeward side, and top of the inlet. This positioning was designed to characterize how each side of the inlet experiences separation (or the lack of) at various angles of attack. All Schuebeler ducts accommodated 6 pressure ports per line, except for the duct for the DS130-HST which accommodated 7. The location of the ports for the the studied EDF ducts are shown in Table 2.3. Its mechanical integration is shown on Figure 2.15.



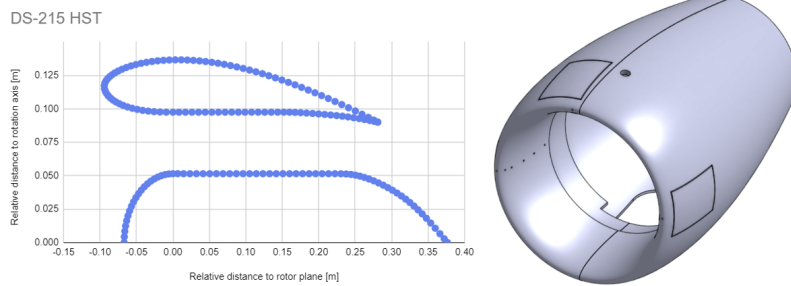
(a) DS51-HST duct geometry



(b) DS82-HST duct geometry



(c) DS130-HST duct geometry



(d) DS215-HST duct geometry

Figure 2.14: Duct geometry and mechanical design for wind tunnel test

Table 2.3: Pressure port location on EDF Inlet

| Port #     | Location Relative to LE (port distance in LE/ inlet length) | Notes         |
|------------|-------------------------------------------------------------|---------------|
| 1          | 0.0                                                         |               |
| Extra Port | 0.04                                                        | Only on DS130 |
| 2          | 0.07                                                        |               |
| 3          | 0.17                                                        |               |
| 4          | 0.40                                                        |               |
| 5          | 0.63                                                        |               |
| 6          | 0.89                                                        |               |

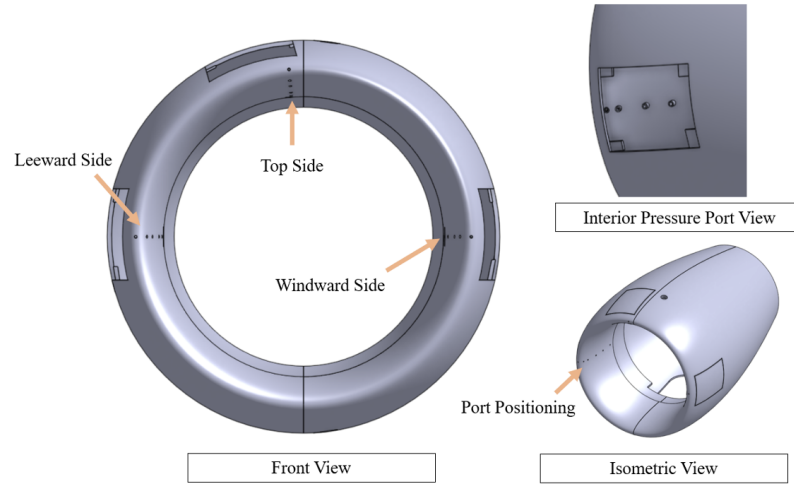


Figure 2.15: Pressure port mechanical integration CAD

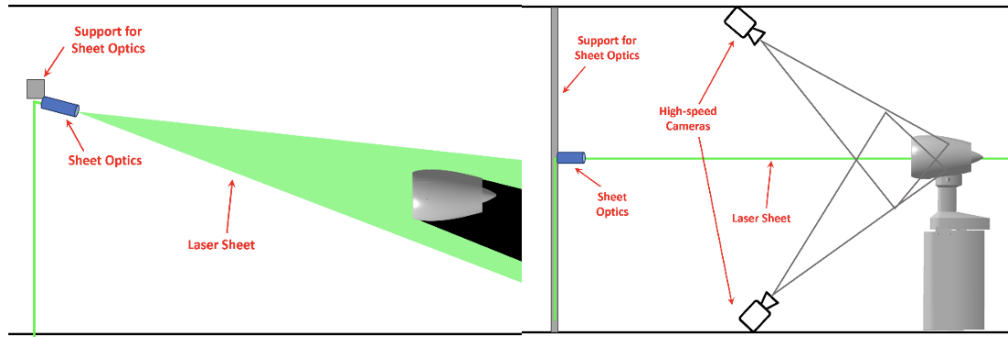
### 2.3.6 PIV Setup for Internal Inlet Measurements

Time-resolved stereo particle image velocimetry (TR-SPIV) was performed at the duct inlet on the DS215-HST EDF to demonstrate the capability and potential of optical flow realization for assessing inlet flow conditions. Figure 2.16(a)(b) show the PIV experimental setup with two Phantom v341 high-speed cameras from Vision Research (2560x1600 resolution, 35 mm CMOS sensor chip, 50 mm lenses, f/4) placed in front of the test article with one mounted above and one below resulting in oblique viewing angles of approximately 45o to 55o. The region of interest (ROI) for this experiment is shown in Figure 2.16(c), which yields a spatial resolution of 5 pixels/mm. A high-speed Nd:YLF dual-cavity pulsed laser from Photonics Industries (527 nm, 30 mJ/pulse @ 1 kHz) was used to generate a horizon-

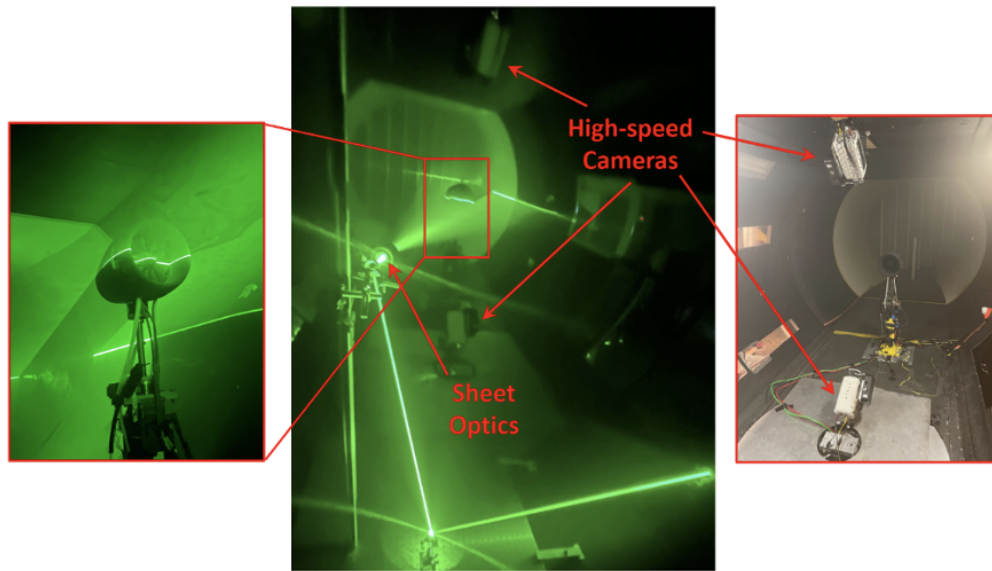
tal laser sheet that intersected the center of each test article. The laser sheet had a thickness of approximately 2 mm. It was created by directing the laser beam from the laser head into the tunnel test section through spherical lenses, optical mirrors, and a -20 mm focal length cylindrical lens at the end to spread the beam. Seeding particles were propylene glycol aerosol with a median particle diameter of 4  $\mu\text{m}$  generated through a Rosco Vapour fog machine. Image acquisition and device synchronization were controlled through a programmable timing unit (PTU) and commanded using DaVis 10 by LaVision. Double-frame images were captured at a frequency of 400 Hz at full resolution for 2.5 seconds, giving a total of 1000 image pairs per camera with a laser pulse separation time of 50  $\mu\text{s}$  for the DS215-HST. This part of the project was done in collaboration with PhD candidate Wei-Han Chen.

### 2.3.7 Test Matrix

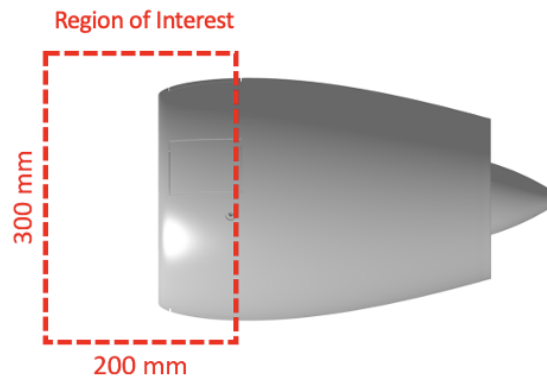
As mentioned in the motivation chapter, EDFs have taken the stage as propulsion systems for conventional aircraft and eVTOL applications. This new push to use the technology could not limit the study to emulate its operation during cruise condition. Still, it would also have to include hover, transition to forward flight, speed reduction maneuver (jet flow into the freestream), and descent. To cover all the phenomena described, the Schuebeler EDFs were rotated between -6 degrees and 180 degrees with respect to the freestream direction with small step intervals in areas of interest. These areas of interest included close to 0 degrees up to post-separation (24 degrees),  $\pm 10$  degrees of the hover position (90 degrees), and the full descent conditions. These attitudes were studied at various airspeeds representative of the flight conditions; for example, the unusual attitudes (above 24 degrees) were only studied at 5 m/s, 8 m/s, and 10 m/s, while the cruise condition attitudes were examined at 10 m/s, 20 m/s, 30 m/s, 40 m/s, and 50 m/s. Depending on the thrust production capability, the tests were terminated when the article could not produce thrust. The test matrix completed for each thruster is shown in the table below. Note that some



(a) Schematic of the experimental setup



(b) PIV setup in Wind Tunnel



(c) Region of Interest

Figure 2.16: PIV setup

thrusters could not complete the desired test matrix due to bearing burn-out, minimum thrust reached, and other mechanical issues associated with the test article. The test matrix



is shown on Figure 2.17.

| Test Article | Angle of Attack (deg)                                     | Air Speed (m/s)  | % of Max RPM      | Max RPM | Notes                     |
|--------------|-----------------------------------------------------------|------------------|-------------------|---------|---------------------------|
| DS51-HST     | -6 to 24 in steps of 2                                    | 10,20,30         | 0.6, 0.7          | 39,400  | Motor failure             |
| DS82-HST     | -6 to 30 in steps of 2; 30 to 70 in steps of 10; 70 to 75 | 5,10,20,30,40,50 | 0.6,0.7, 0.8, 0.9 | 28,500  | N/A                       |
| DS130-HST    | in steps of 5; 75 to 87 in steps of 2; 88 to 93 in steps  |                  |                   | 20,000  | done only for 0.6% of max |
| DS215-HST    | of 1; 93 to 105 in steps of 2; 110 to 180 in steps of 10  |                  |                   | 14,000  | N/A                       |

Figure 2.17: Test Matrix

## 2.4 Isolated EDF (Clark-Y Duct)

### 2.4.1 Test Rig

As mentioned, the isolated EDF tests shown in the previous section were sponsored by Whisper Aero and featured unique duct designs. To create a baseline for the integration tests and validate that the rig construction would work properly, a rig was designed and tested. The rig features all the same technology present on the other isolated and integrated tests. Figure Figure 2.18(a) shows the design of the isolated EDF rig in the wind tunnel test section, and Figure 2.18(b) shows the definition of the axis. The aerodynamic fairing is integrated to keep the loadcell measurements isolated from drag created by the offset post and to maintain the loadcell isolated from the flow. The test matrix

### 2.4.2 Test Matrix

The test matrix is shown in Table Table 2.6; a range including high angles of attack (AOA) was selected to allow a study of the propulsor during the transition between hover and forward flight, where high angle of attack is expected.

Table 2.4: Experimental Test Matrix for isolated EDF validation test

| Isolated EDF Test Matrix  |                 |                        |
|---------------------------|-----------------|------------------------|
| Freestream Velocity (m/s) | RPM             | Angles of Attack (deg) |
| 0                         | 10k : 10k : 30k | -35 : 5 : 35           |
| 5                         |                 |                        |
| 10                        |                 |                        |
| 15                        |                 |                        |

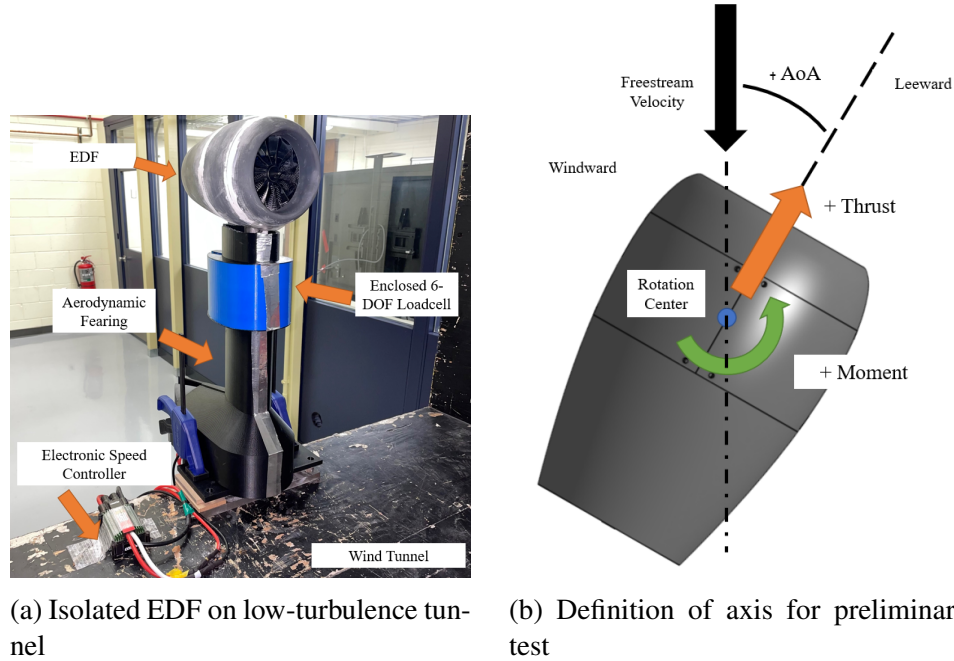


Figure 2.18: Preliminary test rig for Clark-Y duct baseline

## 2.5 Symmetrical Airfoil Integrated EDF Test Rig Design and Test Matrix

The overarching goal of the thesis is to understand the effects that a wing-EDF integration method might have on the fundamental aerodynamics and performance of the EDF system. An aero-propulsive integration was done on a symmetrical wing as a first step in the investigation. The goal of using a symmetrical wing was to understand not only how a leading-edge or trailing-edge integration affected the performance of the EDF but also what the effects would be if that same method were employed on the wing's upper surface or lower surface. This section describes the development of the test rig and some of the issues encountered. The tests for this thesis section were done in the Low Turbulence Wind Tunnel.

### 2.5.1 Test Stand Design and Manufacturing

Force and moment data of the EDF system were obtained by having the EDF attached in a separate load path connected to a 6DOF force-torque sensor. The EDF load cell was

mounted directly onto the wing spar, as illustrated in Figures Figure 2.19(a) and Figure 2.19(b) for the trailing and leading edge EDF integrations, respectively. This setup provided the unique capability to decouple the forces of the EDF from the ones of the entire system. The EDF was equipped with an electrical power sensor and an RPM sensor to characterize its performance thoroughly.

Figure Figure 2.19 shows the test rig for the leading-edge integration platform inside the wind tunnel and each integration's mechanical design. Between tests, the EDF integration zone was the only zone changed. The remaining wing sections featured the same airfoil cross-section as the integration platform. They extended into the boundary layer of the wind tunnel walls to reduce 3D effects on the propulsor, as shown in Figure Figure 2.19(c). The test rig was placed at the exhaust of the tunnel to minimize facility effects from the EDF's jet exhaust impinging on the wind tunnel walls, as the EDF's jet exhaust was expected to be between 80 and 100 m/s. This installation permitted the jet to exit with minimal interaction.

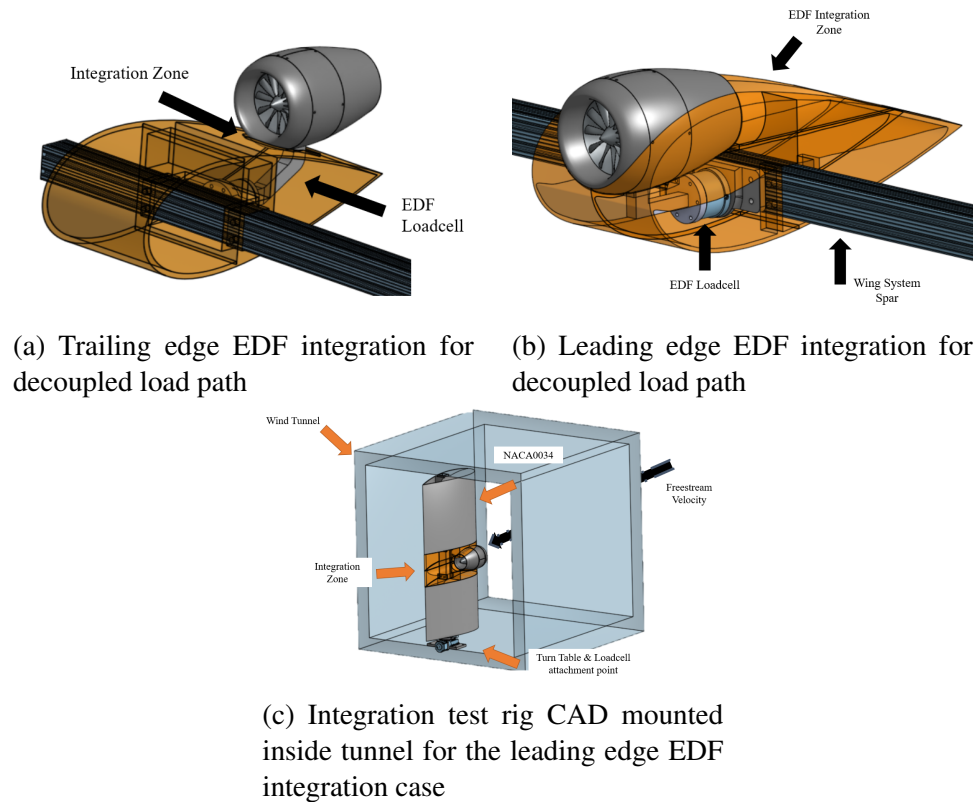


Figure 2.19: EDF integration mechanical design and tunnel integration

### *Manufacturing and Assembly*

The integration zone on the leading edge integration method, denoted in orange on Figure 2.19, was manufactured using FormLabs Draft resin. This print ensured tighter tolerance and finish for the complicated enclosure needed, this is shown on Figure 2.20. The integration zone for the trailing edge case was printed using a conventional FDM printer. The piece was later post processed by sanding and applying a surface finish resin. Both integrations are modified NACA0034 airfoil. For the leading edge integration, the leading edge of the duct's inlet is flushed with the wing's leading edge. In the case of the trailing edge, the exhaust of the duct is flush with the trailing edge of the wing. The position of the duct is adjusted vertically so that the inlet is integrated with the wing surface while being parallel with the chord line.

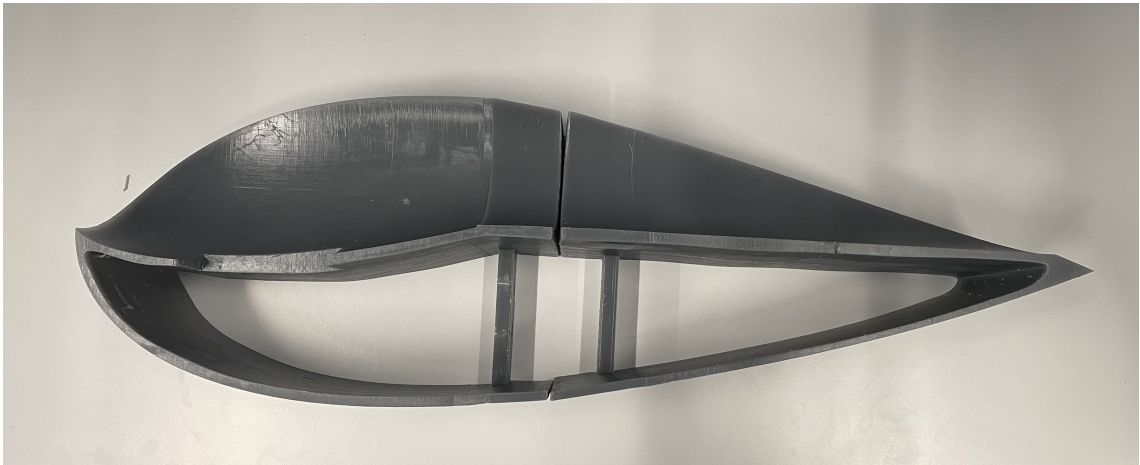


Figure 2.20: Leading edge integration resin wing integration

To reduce possible 3D effects on the EDF and the integration zone, two NACA0034 wing sections were manufactured using a wooden rib structure and monokote coating. The internal structure is shown on Figure 2.21. A building support structure was constructed on the bottom of the wing to make assembly more accurate. This support structure was later cut out, leaving only the airfoil shape.

Figure 2.22 shows the mechanical drawing of the test rig. Note that the support structure

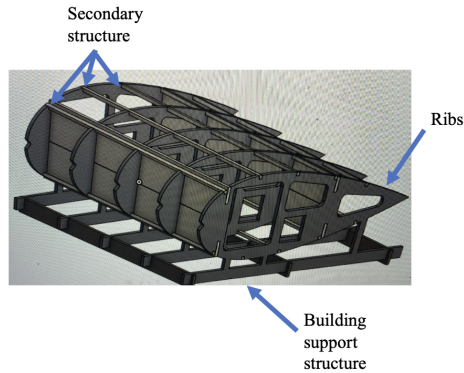


Figure 2.21: Remaining wing section internal structure

is cut off when manufactured. The wing extends up to the stepper motor and encloses the root loadcell. Even though the loadcell measurements were not feasible (as discussed in the Issues discussion subsection), the loadcell was left there as manufacturing another structure to account for the loadcell height was not possible. The voltage outputs of the loadcell were measured to ensure that the sensor was not overloaded.

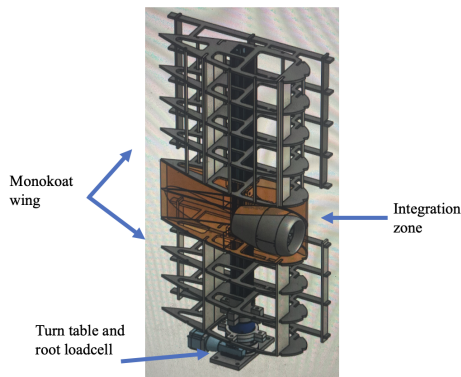


Figure 2.22: Complete wing construction with support structure attached

The gap between the wind tunnel's floor and the wing's bottom was 2.3 in, while the top of the wing to the roof was 0.5 in. The Low-Turbulence wind tunnel has a measured boundary layer height of 3 in. Immersing the edges of the wing into the boundary layer of the wind tunnel was believed to help with reducing 3D effects, this was not verified through any experiment.

Figure 2.23 shows the wing sections completed (left) and only the structure (right).

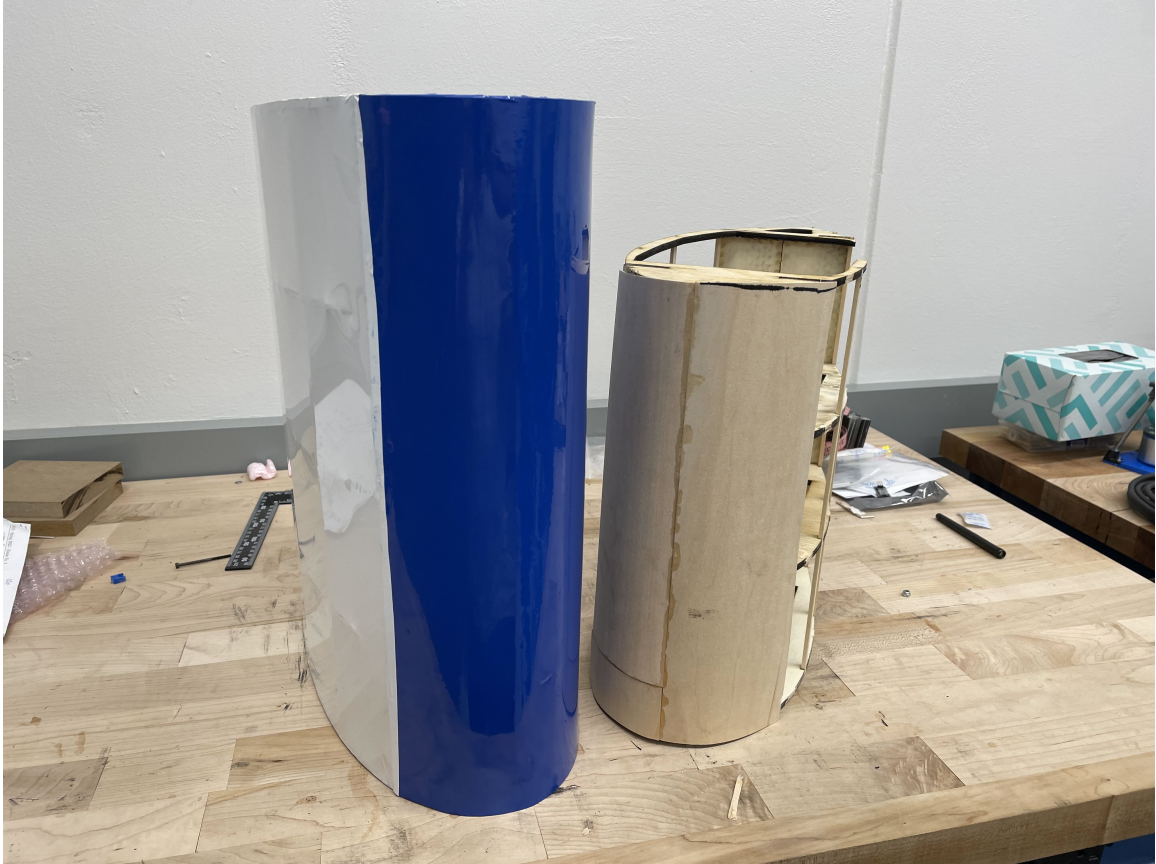


Figure 2.23: Constructed wing sections monokote applied (left) and bare structure (right)

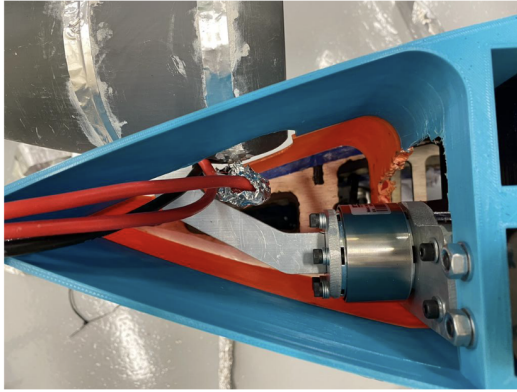
The monokote was applied in 2 different colors. Blue shows the upper surface of the wing, while the lower surface is white.

As mentioned, a loadcell is placed to decouple the EDF forces and moments from the systems. The goal of this was to study what effects the integration had on the EDF performance.

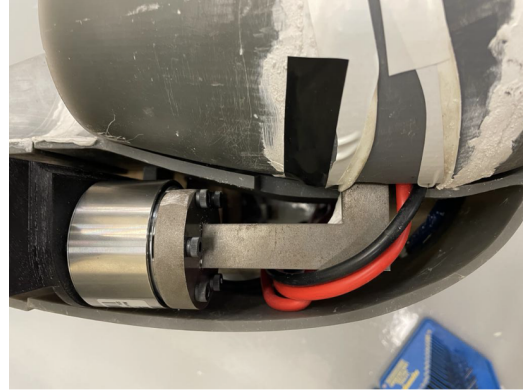
Figure 2.24 shows how the loadcell is attached for both the leading edge and trailing edge integration. In both cases, the anchor side of the loadcell is attached to the spar, and the measuring plate is attached to the EDF. Note that the loadcell is carefully placed to not touch the wing section for reduced measurement contamination. The tight placement of the loadcell also shows the reason for selecting a NACA0034 airfoil as the wing section. While the trailing edge integration leaves plenty of space for the loadcell, the leading edge barely has space for it. The airfoil section was selected to remain the same during that



testing campaign to reduce number of independent variables. The wires were taped to the wing structure to minimize any loads that might come from tugging the wires when moving between angles of attack. Figure 2.25 shows the assembled rig positioned in the low turbulence wind tunnel exhaust.

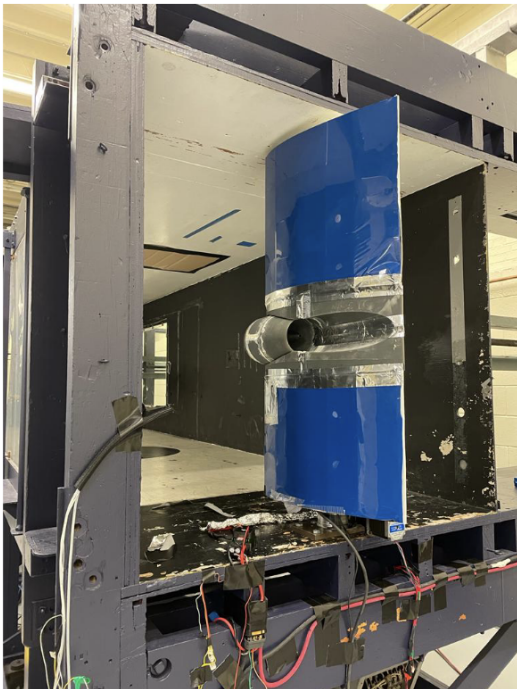


(a) Trailing edge EDF loadcell integration

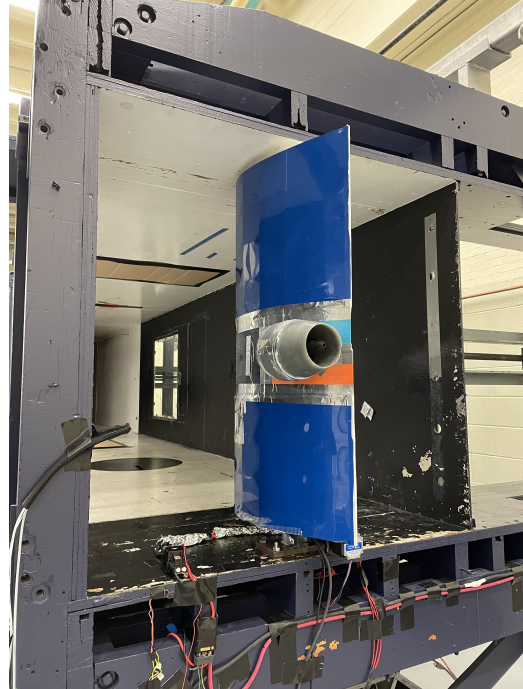


(b) Leading edge EDF loadcell integration

Figure 2.24: EDF loadcell integration



(a) Leading edge integration



(b) Trailing edge integration

Figure 2.25: Assembled rig at the exhaust of the low turbulence wind tunnel

### 2.5.2 Issues with the Rig and Mitigation

This subsection describes two issues with this construction that generated issues when taking data. The two discussion points were issues with the loadcell located at the root and EMI between the power wires and the EDF loadcell.

#### *Root Loadcell Issues Discussion*

Initially, the scope of the test was to study both the EDF loads and the aero-propulsive system loads separately. For this, the EDF loadcell was attached to the wing main spar, which was later connected to a loadcell at the root of the structure. Through this construction, the EDF loads could be measured independently from the system while the root loadcell still sensed the loads from the EDF. The positioning of the root loadcell is seen on Figure 2.19(c).

In theory, 6-DOF force torque sensors resolve any forces and moments as long as these remain within the range of the sensor's calibration. Note that the factory calibrations are done by applying known loads and moments near the loadcell origin. Based on conversations with the manufacturers and analysis of the calibration documents, the most significant moment arm supported by the calibration is 20 cm from the origin of the measurement plate. With the setup described in this section, a distributed load was applied using an arm of 1 m in length, generating issues of crosstalk between the measurements. To investigate this problem, point loads were applied at various distances from the measurement plate origin. Point loads (under 10N) applied more than 25 cm off-axis from the measurement origin would generate faulty results. The faulty results would be characterized by crosstalk between the  $F_x$  and  $F_y$  measurements by both showing the same (and erroneous) reading.

For future designs, conversations with the manufacturers should occur to discuss the specific usage of the loadcell and request a special calibration. Other suggested approaches were creating an offload using 1 DOF force sensor to relieve the loadcell from any significant off-axis moment. Due to the time constraint on this project, this testing campaign



reduced its scope to obtain only EDF loads. Resolving the forces was left for the following entry, described in this thesis's next section.

### *Electro Magnetic Interference (EMI) Reduction*

The tight construction and the need to run the 3-phase power cables in parallel with the loadcell cables caused EMI, rendering integrated measurements unusable. Heavy-duty aluminum foil was wrapped around critical components to mitigate this effect, and the power wires were routed outside the wing. Wing loads are outside the scope of this work due to fundamental issues with the placement of the root loadcell; hence, disturbing the flow away from the EDF was deemed acceptable. Figure Figure 2.26 shows the described construction for EMI reduction.



Figure 2.26: Power wires running outside of wing for EMI reduction

### 2.5.3 Duct Geometry and EDF

The decided duct geometry is a revolved Clark-Y airfoil cross-section rotated pitch up by 2.3 degrees. This rotation is implemented to maintain a flat profile in the exhaust section. Keeping the exhaust cross section constant, hence not including any diffusion or contraction, reduced the number of variables for the integration tests. Figure Figure 2.27 shows the duct geometry.

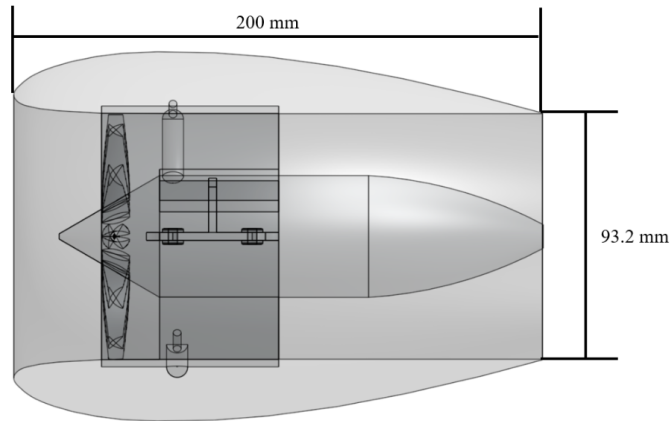


Figure 2.27: Tested EDF Geometry

The EDF used for the tests is a Schuebeler Technologies DS51-HST EDF. Its characteristics are outlined on table Table 2.5

Table 2.5: DS51-HST Characteristics

| Shuebeler DS51-HST |                    |
|--------------------|--------------------|
| Fan Swept Area     | 51 cm <sup>2</sup> |
| Weight             | 640 g              |
| Static Thrust      | 53 N               |
| Exhaust Speed      | 93 m/s             |
| Total Efficiency   | 71 %               |

### 2.5.4 Axis Definition and Transformations

The primary focus of the thesis is to understand the integration's effects on EDF performance and output. The measurements on the loadcell were translated to the origin of the

rotor plane. Equation 2.2 represents the transformation done to the leading edge integration;  $no_{offsetofintegration}$  is 0. Equation 2.3 shows the transformation matrix for the trailing edge integration; similarly, the  $y_{offset}$  in that case is 0.

$$F_{Transformed} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & z_{offset} & y_{offset} & 1 & 0 & 0 \\ -z_{offset} & 0 & x_{offset} & 0 & 1 & 0 \\ y_{offset} & -x_{offset} & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} \quad (2.2)$$

$$F_{Transformed} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & z_{offset} & -y_{offset} & 1 & 0 & 0 \\ -z_{offset} & 0 & x_{offset} & 0 & 1 & 0 \\ y_{offset} & -x_{offset} & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} \quad (2.3)$$

Figure 2.28 shows the axis definition for both studied integrations. The mounting on those 2 cases is similar, just rotated 180 degrees around the y-axis.

As mentioned before, the symmetric nature of the installation permits for the study a lower surface and upper surface integration with the same rig. To easily represent each integration in one graph in the result section, the negative angles of attack represent the duct being integrated on the upper surface of the wing while positive angles of attack represent a lower surface integration. This is shown on Figure 2.29.

### 2.5.5 Test Matrix

The test matrix was designed to explore the EDF behaviour during cruise flight and late transition angles (i.e., for eVTOL applications). The angles of attack were limited by ge-

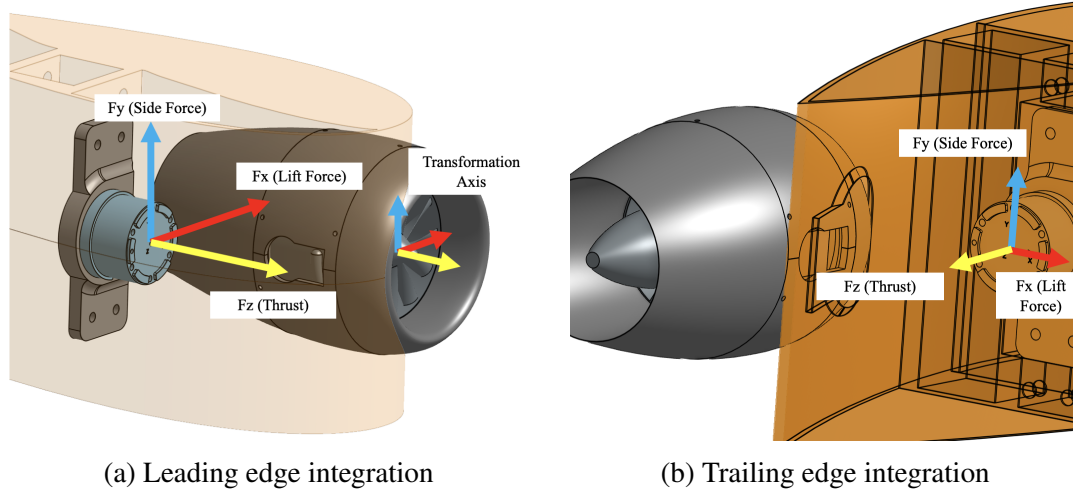


Figure 2.28: Axis definition

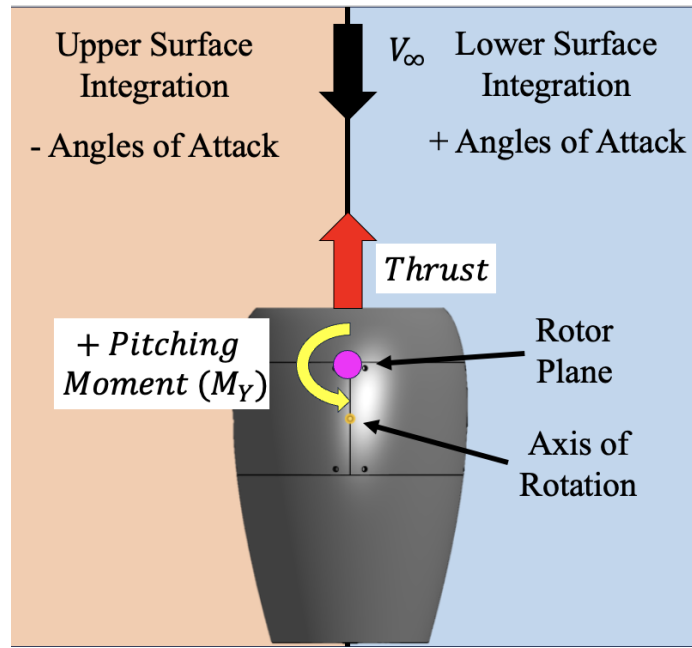


Figure 2.29: Upper surface and lower surface integration axis definition

ometric constraints of the test facility and turn table. Using this test matrix resulted in various advance ratios. The highest advance ratio tested was 0.51. The same test matrix was applied to all studied configurations. The associated advance ratios ( $J$ ) for each studied configuration are shown in Table 2.7.

Advance ratio ( $J$ ) is denoted in propeller terms as the EDF acts more as a propeller (axial flight) than a rotor, which usually operates in edgewise flight. Equation 2.4 shows

| Test Matrix               |               |                        |
|---------------------------|---------------|------------------------|
| Freestream Velocity (m/s) | RPM           | Angles of Attack (deg) |
| 5, 7, 10, 12              | 15k, 20k, 25k | -24 to 24, steps of 2  |

Table 2.6: Experimental test matrix for EDF integration test

| Airspeed<br>(m/s) | RPM    |        |        |       |
|-------------------|--------|--------|--------|-------|
|                   | 15,000 | 20,000 | 25,000 |       |
|                   | 5      | 0.215  | 0.161  | 0.129 |
|                   | 7      | 0.301  | 0.226  | 0.181 |
|                   | 10     | 0.431  | 0.323  | 0.258 |
|                   | 12     | 0.516  | 0.387  | 0.309 |

Table 2.7: Studied advance ratios

the equation for advance ratio ( $J$ ); note that  $V_{inf}$  is the freestream velocity,  $n$  is revolutions per second, and  $D$  is the rotor diameter.

$$J = V_{inf}/(nD) \quad (2.4)$$

## 2.6 Full Transition and High Speed Wing Integrated EDF Test Rig Design and Test Matrix

The last piece of the experimental study involved a rig re-design to be able to properly measure the system loads and to be able to test on the Harper tunnel. Note that while the rig includes the capabilities to measure pressure distribution over the wing system and the loads of the aero-propulsive system those results are out of the scope of this work. The design of the rig is still discussed as the loadcell placement provides a solution to issues encountered previously and could be beneficial for experimentalists in the future.

The goal of this test was to explore the effects that complete transition, as hover to cruise or cruise to descent, had on the thrust output of the EDF system. To achieve this the

test was broken into two tunnel entries: one at the Low-Turbulence wind tunnel and one at the Harper wind tunnel. The goal of the low-turbulence tunnel entry was to study the early transition (70 deg to 110) and descent cases. The tunnel is designed to hold steady freestream velocities up to 2 m/s. The low airspeed cases are representative of what a vehicle would experience during those stages of flight. The second test, conducted at the Harper wind tunnel, focused on studying the cruise, stalls, and high angle of attack behaviors of the integrated system. This section describes the rig design for both test sections and changes to the airfoil geometry.

### 2.6.1 Test Stand Design

Modularity is one of the key design factors on this rig. Due to time constraints on the project, the rig had to be able to transition between the low-turbulence tunnel and the Harper tunnel without major redesign. Similar to the symmetrical wing test, the EDF is integrated on a 3D printer piece that is referred as the integration zone. The difference is that now, the integration zone is isolated from the main wing spar and connected via two loadcells. The integration zone represents under 15% of the total wing span of the article put into the Harper tunnel. Isolating the integration zone was done to more easily observe the effects that the EDF had on the system loads. Figure 2.30 shows the rig CAD mounted on the low-turbulence wind tunnel. The rig for the Harper tunnel is exactly the same exempt the wings extending from the integration zone to the boundaries are longer. The rig has 2 loadcells to measure the system loads and an integrated loadcell attached to the main spar to measure the EDF loads independently. Similar to the Symmetrical airfoil testing rig, the turn table actuates the changes in angles of attack. In this case, the rig was attached also to the ceiling of the wind tunnel via a bearing that permits it to spin freely but not translate. This mitigated the issues of having the rig as a cantilevered beam, reducing vibrations. The internal EDF loadcell is attached in the same way it was in the symmetrical wing test.

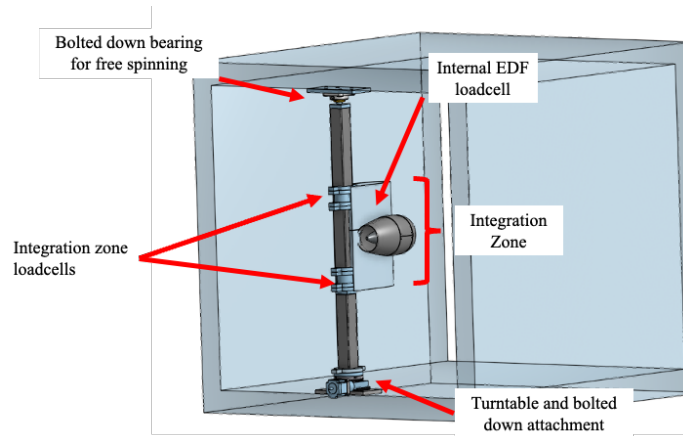


Figure 2.30: Rig mechanical design mounted on Low-Turbulence wind tunnel

### *Wing Section and EDF*

The new wing section is an inverted Clark-Y modified to have 18% thickness to chord ratio. The increase in thickness was needed to fit all the internal measurement devices. With this new wing section, the measurement equipment fit properly and no changes had to be done to accommodate the exhaust of the leading edge integration, enhancing the comparability of both integration methods. While this airfoil doesn't represent a wing section that would be seen on an experimental aircraft, it does provide similar characteristics to assess the aerodynamic effects that a wing section will have on an EDF. The wing section with the EDFs integrated is shown on Figure 2.31. The wing section chord is 50 cm. The duct EDF used during these tests is the same as the one used in the symmetrical wing tests.

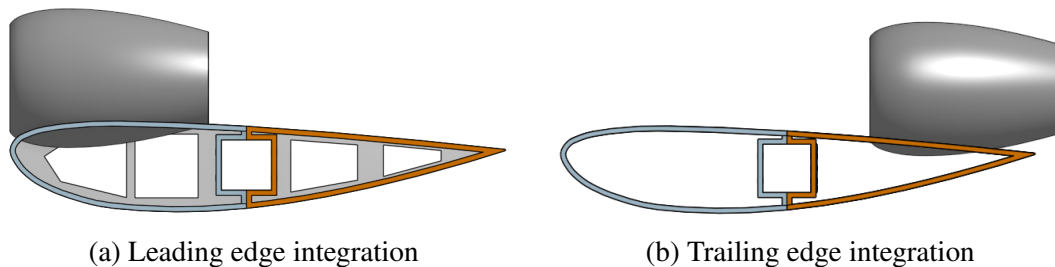


Figure 2.31: EDF integrated into Clark-Y 18% thickness wing section

## *Manufacturing*

The rig was built using 2 in x 2 in aluminum square tubes as the main spar. These were welded to mounting plates that bolted down to the loadcells or EDF mounting plates. The integration zone is built with FDM 3D printed parts, resin prints were not possible due to maintenance issues with the on-campus resin printers. The FDM parts were sanded and smoothed with an epoxy to have a smooth surface finish. The wing extensions that covered the non-load-measuring portion (everything outside the integration zone) were foam cut and laminated with 2 carbon fiber 3K weave fabric. The epoxy used for hardening was the west system 206 slow hardener and 105 epoxy resin. This combination permitted a cure at room temperature and a working time of 25 mins. Figure 2.32 shows some images from the layup. The wings for Harper were too big to vacuum bag, so they were cured at room temperature and then smoothed.



(a) Wings used for low-turbulence tunnel ready to vacuum bag



(b) Wings used for Harper tunnel curing at room temperature

Figure 2.32: Wings used for Harper tunnel curing at room temperature

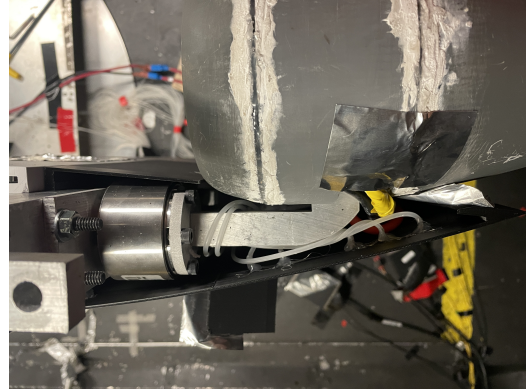
Figure 2.34 shows both integrations inside the 3D printed wing section. The loadcell is completely isolated from the wing section and attached at the wing's spar. This construction ensures that the decoupled EDF loads are reliable.

The placement in the wind tunnel section is the same as the one described in the isolated EDF tests. Figure 2.34 shows the integrations inside the Harper and low turbulence tunnels.





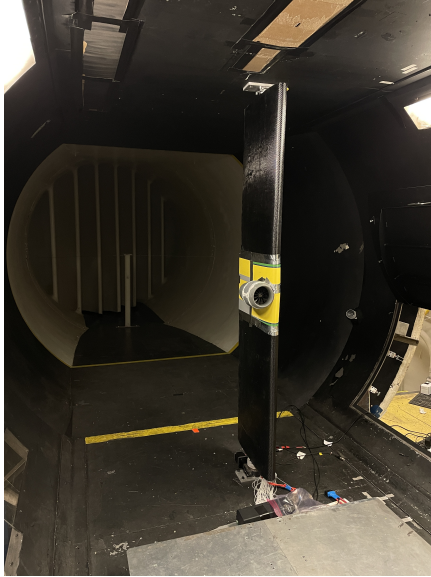
(a) Leading edge integration



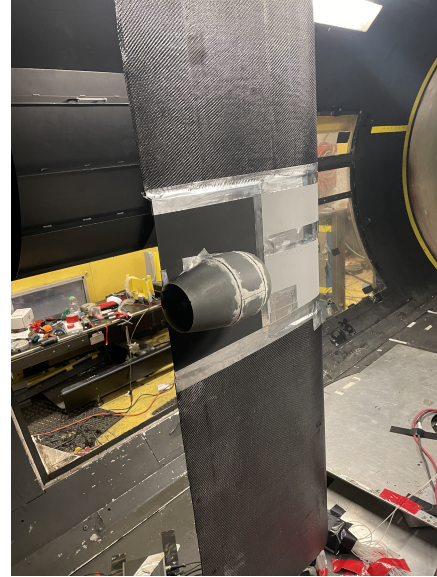
(b) Trailing edge integration

Figure 2.33: Integrated EDF on 3D printed wing section

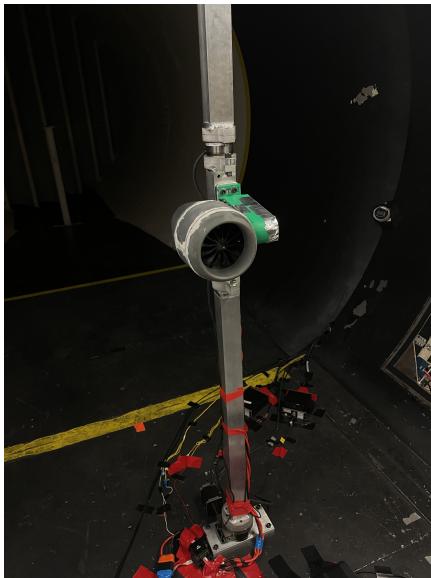
Note that the wing extends to the boundary of the tunnel. For the Harper tests, the top of the wing has 0.5 in clearance with the wall and the bottom a clearance of 2.5 in. In the case of low-turbulence, the top has a clearance of 1 in and the bottom has a clearance of 2.5 in.



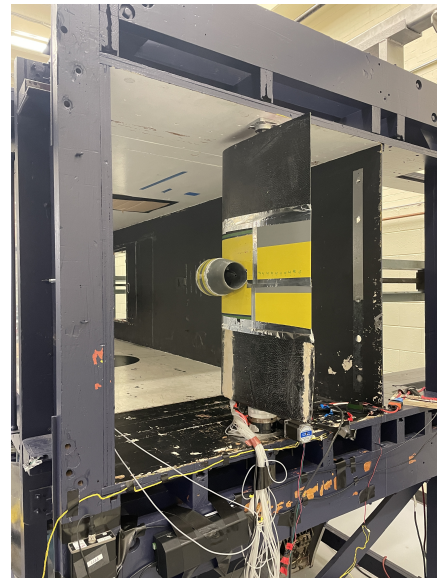
(a) Leading edge integration



(b) Trailing edge integration



(c) Isolated



(d) Leading edge integration (Low-Turbulence Wind Tunnel)

Figure 2.34: Integrated test rigs on both Harper and Low-Turbulence Tunnel

### 2.6.2 Test Matrix

The test matrix for this test is divided into 2: the matrix of the low-turbulence wind tunnel and the Harper wind tunnel. The goal of the tests at the low-turbulence wind tunnel is to study the initial stages of transition, airbreak maneuver, and the descent case for both

integrations. The low-turbulence tunnel can hold airspeed as low as two m/s and provide fine airspeed adjustments needed for this test. A fine set of angles are studied near the edge wise flight condition, ranging from 70 deg of angle of attack to 110 degrees in steps of 2. A coarser matrix is done for the airbreak maneuver and descent case, ranging from 120 deg to 180 in steps of 10 deg. The matrix is shown on Table 2.8. The matrix for the Harper tunnel is designed to study the system in a cruise condition, stall regimen, and high angles of attack. The airspeeds studied in this section are 10 m/s up to 20 m/s. The angles are studied finely between -2 to 46 degrees in steps of 2 degrees. Both tests study the same RPMs. The test matrix is shown on Table 2.9

| <b>Low Turbulence Wind Tunnel</b> |                   |                                              |
|-----------------------------------|-------------------|----------------------------------------------|
| <b>Airspeed (m/s)</b>             | <b>RPM (kRPM)</b> | <b>Angle of Attack (deg)</b>                 |
| 2, 4, 6, 8, 10                    | 25, 28, 32        | 70 to 110 steps of 2; 120 to 180 steps of 10 |

Table 2.8: Test matrix for Low-Turbulence wind tunnel

| <b>Harper Wind Tunnel</b> |                   |                              |
|---------------------------|-------------------|------------------------------|
| <b>Airspeed (m/s)</b>     | <b>RPM (kRPM)</b> | <b>Angle of Attack (deg)</b> |
| 10, 15, 20                | 25, 28, 32        | -2 to 46 in steps of 2       |

Table 2.9: Test matrix for Harper Tunnel

### *Issues with the Rig*

The updates with the rig permitted the taking of loads on the wing section without signs of cross-coupling. This subsection focuses on discussing two critical issues in construction. The first issue was the problem of shaft miss alignment. Having the turn table and a bearing on the top permitted the beam to revolve freely, but slight miss alignments on the

mounting of both ends created very high internal loads; for the low turbulence tests, the miss alignment caused over torque to the turn table. To mitigate this, it is suggested that a shaft coupler be put on the bearing side to alleviate the miss alignment while still holding the boundary condition. The second issue was one of flutter. Due to the requirement of having a loadcell for the EDF, the integration zone of the wing had to be hollow plastic. This was okay for the airspeeds up to 20 m/s; for 25 m/s and above, the wing fluttered post-stall. To avoid this, it is suggested to structurally enhance the plastic structure by adding a composite layup for strength.

## **2.7 Research in Flight's FlightStream**

Research in Flight's FlightStream software is being used. FlightStream is a viscous surface vorticity solver that calculates forces and moments based on the vortex shedding from an unstructured surface mesh. The software can also resolve laminar and turbulent boundary layers with a flow transition model described by Dvorak et al. [8]. This extended capability permits the study of separation effects, as noted by DiMaggio et al. in their research of hybrid wind body vehicles using FlightStream [9]. Through a NASA STTR program, FlightStream developed an unsteady vorticity solver that can be applied to rotating reference planes, validated by the company against NASA TN D-4142 ducted fan, BlackHawk flight test data, and co-axial test data. The company validated the software's boundary layer ingestion modeling capability against the NASA LaRC experimental measurements [10].

## CHAPTER 3

### RESULTS AND DISCUSSION

Each test described in Chapter 2 is discussed individually. The results are later addressed to draw more generalist conclusions that help answer the fundamental questions to be addressed following the thesis proposal. Validation results are also presented in this chapter; these include a basic validation of the FlightStream software and a validation experimental run to verify the data collection system worked before the three primary wind tunnel entries. The first entry focused on studying the EDFs in isolation and understanding how these effects scale. The results from the entry include inlet and exhaust pressures, 6-DOF forces and moments (with respect to the origin of the rotor plane), and performance comparison between EDFs. For brevity, the section will only show forces and moments for unusual angles of attack for 2 EDF sizes: DS82 and DS215. The second section focuses on the results of the symmetric wing study in the Low Turbulence Wind Tunnel. These results focus on the thrust and pitching moment of the duct, as they are the dominant force/moment in the system. The effects of integrating the EDF on the lower surface or the upper surface are investigated and discussed. Finally, the EDF integrated on the upper surface of an inverted Clark-Y airfoil is studied for the full transition cases and higher airspeeds (up to 20 m/s) in the Harper tunnel. Through this section, the percentage difference calculated is shown by Equation 3.1

$$\%Difference = abs(V1 - V2)/((V1 + V2)/2) \quad (3.1)$$

#### 3.1 FlightStream Airfoil Aerodynamics Validation

Using FlightStream gives a lens into flow conditions that are hard to obtain experimentally due to visual inaccessibility or flow disruption that would provide inaccurate results.

An in-house validation was performed using a NACA0012 airfoil section wing to ensure the boundary layer and the separation were correctly modeled. Figure 3.1 presents the results from the validation case, compared to experimental data from Theory of Wing Sections [11]. The software can adequately model the linear region, maximum lift coefficient, and stall location. The post-stall behavior follows similar trends to the experimental data set, but the lift coefficient post-stall is over-predicted. This behavior shows that FlightStream predicts the separation over the wing correctly.

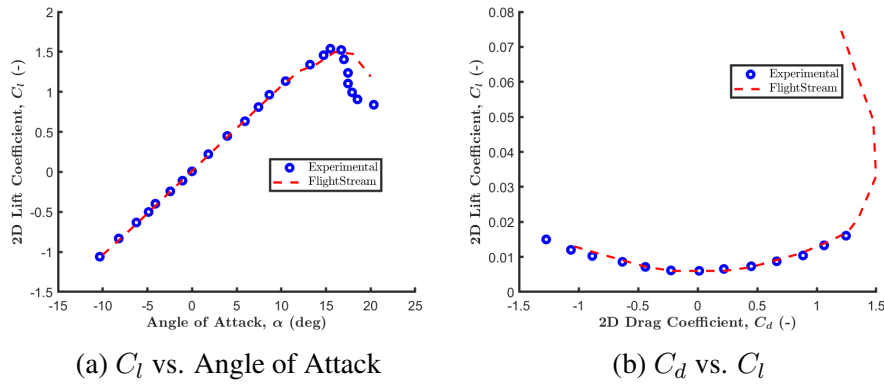


Figure 3.1: In-house FlightStream Validation Case for NACA0012 at  $RE = 1.2M$

### 3.2 Isolated EDF Test

This subsection explores the results of each of the 6-DOF forces and moments observed on the Schuebeler EDF; these included DS51, DS82, DS130, and DS215. Inlet and exhaust pressures are discussed as well. This section shows representative result plots and a discussion on the behavior. An exhaustive list of result plots is shown in Appendix B. Due to time constraints and the extensive test matrix, only one repeatability run was conducted on each EDF.

#### 3.2.1 Thrust

The first portion focuses on studying the thrust of the HST Fans at various angles of attack, airspeeds, and RPM. Note that the legend shows the percentage of the maximum RPM of

the EDF quoted in Figure 2.17.

From the sequence presented, it can be observed that the influence of the freestream velocity is affected by the ratio of the inflow velocity over the freestream velocity. At low air speeds, it is observed that the thrust of the propulsor is independent of the angle of attack. The dominance of the inflow velocity over the freestream also causes the duct to exhibit delayed stall behaviors. For example, at the low freestream velocities, the duct stalls beyond -24 degrees of angle of attack, as seen in Figure 3.2; this is attributed to the dominant suction effect from the fan over the inlet lip. This effect can be observed more clearly on the plot showing a freestream velocity of 20 m/s. The inlet stall angle, characterized by the sudden loss of thrust, drifts as RPM increases. This phenomenon is shown in the DS82 plot in Figure 3.3 (top right); at the lowest RPM setting, the lip stall angle is located at 18 deg; this stall angle moves to 22 degrees for the following RPM setting. The stall angle moves past 24 degrees for the higher RPM settings. Similar effects can be observed on the DS130 and DS215.

The EDF was also studied at unusual attitudes, like what a quad-copter or an eVTOL like the Lilium Jet, equipped with ducted fans, would experience. Figure 3.4 shows the DS82 and the DS215 thrust output at various angles of attack, from a cruise condition (0 degrees) to a full descent condition (180 degrees). An important takeaway is the consistency of the thrust output of the EDF at all angles of attack. Taking the 90 degrees case (edgewise flight), the thrust lost when going to a complete streamwise flight (0 degrees), the thrust loss is between 12% and 15%. The thrust increase between the same baseline and the full descent case ranges between 5% and 0%. The effect on the exhaust of the thruster is less aggressive for the larger-sized fans.

### 3.2.2 Normal Force

As defined previously, the normal force is the force acting perpendicular to the duct's centerline. Figure 3.6 shows the results from this axis. Figure 3.6 shows that the normal force

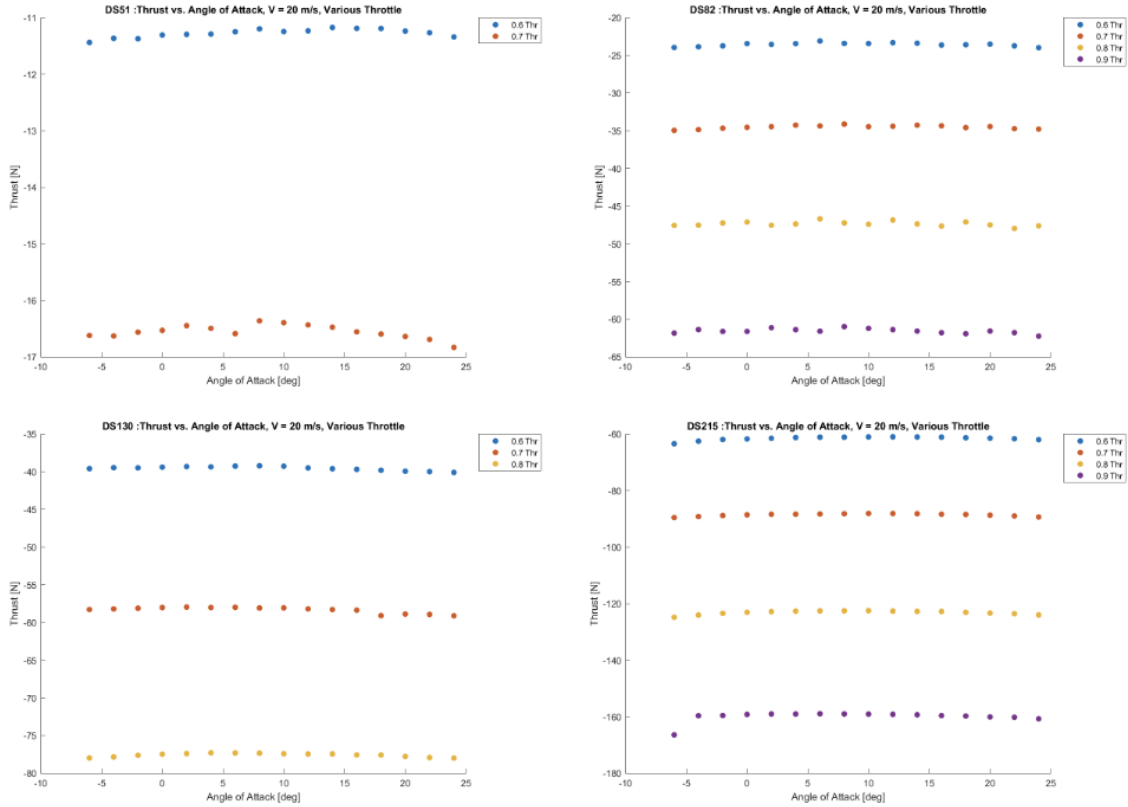


Figure 3.2: Thrust: HST Fans at freestream velocity 20 m/s, Thr on legend represents maximum RPM

is independent of thrust and is mainly affected by the angle of attack and the freestream velocity. Figure 3.5 shows the results for unusual attitudes up to 180 degrees showing similar behavior. The peak of the normal force occurs at 90 degrees and then returns to a similar value to the cruise condition once it reaches 180 degrees.

### 3.2.3 Side Force

The side force, in theory, should be close to zero for all angles of attack as it is a symmetric cylinder, and as expected, the trends observed are dependent on airspeed, not on the RPM of the EDF. It is hypothesized that this side force is generated due to the interference from the test stand. The stand generates substantial blockage in the lower portion of the duct while the top remains clear, causing a pressure differential and, hence, a force. Figure 3.7 shows that the side force increases at high angles of attack because, at higher angles, the duct



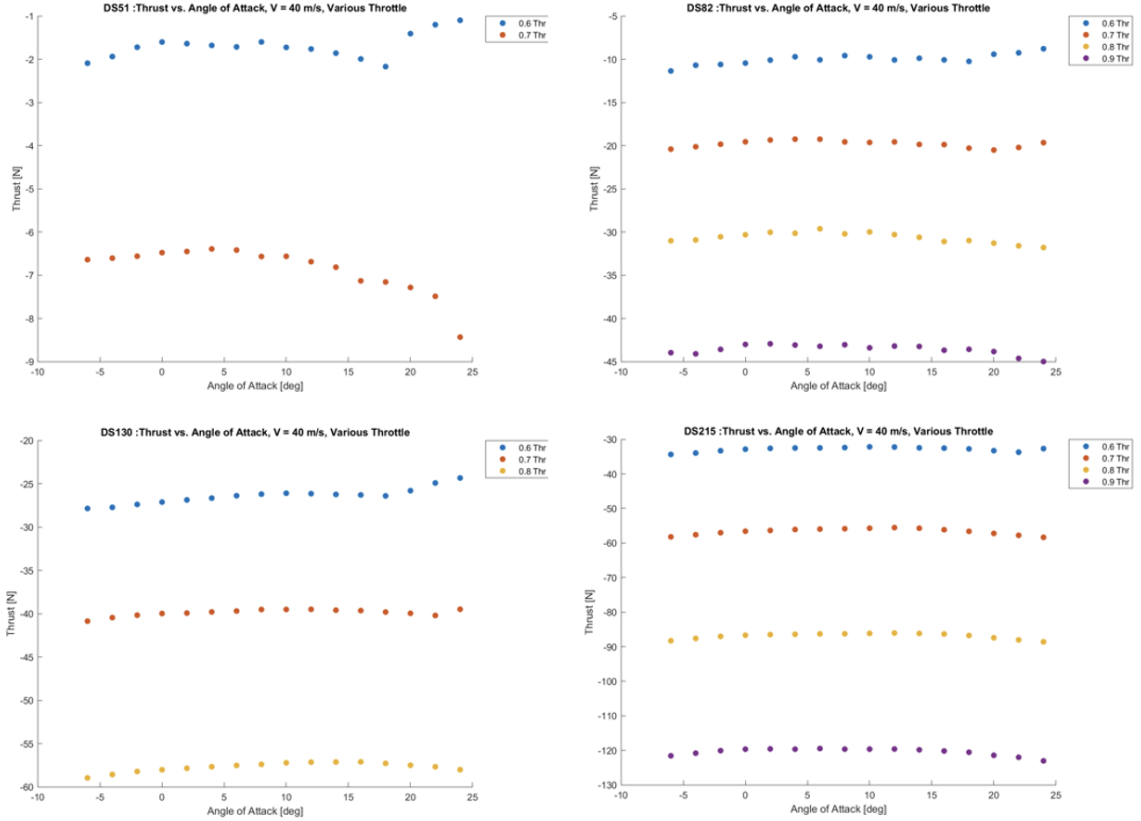


Figure 3.3: Thrust: HST Fans at freestream velocity 40 m/s, Thr on legend represents maximum RPM

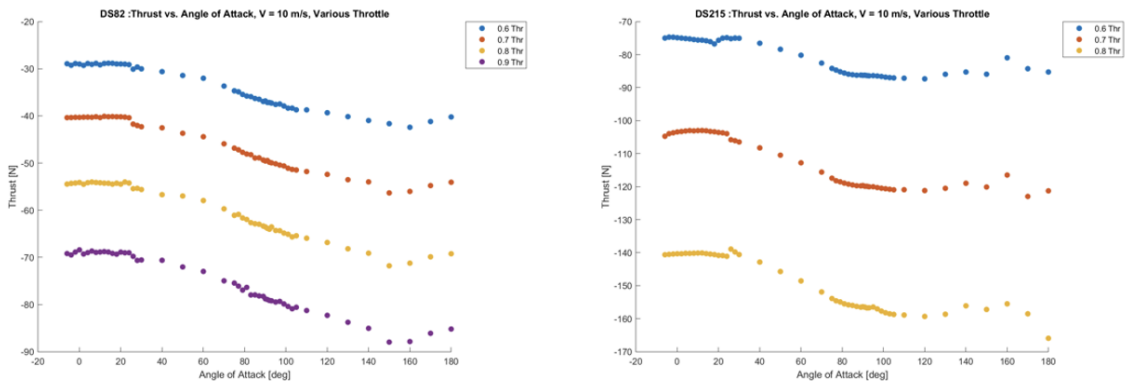


Figure 3.4: Thrust: HST Fans at unusual angles DS82 and DS215, Thr on legend represents maximum RPM

acts as a cylinder in the freestream, coupled with the disturbance the side force is created.

Figure 3.8 shows the most significant magnitude of the force at 90 degrees angle of attack.

While this force was generated mainly by test stand interference, it is worth noting that

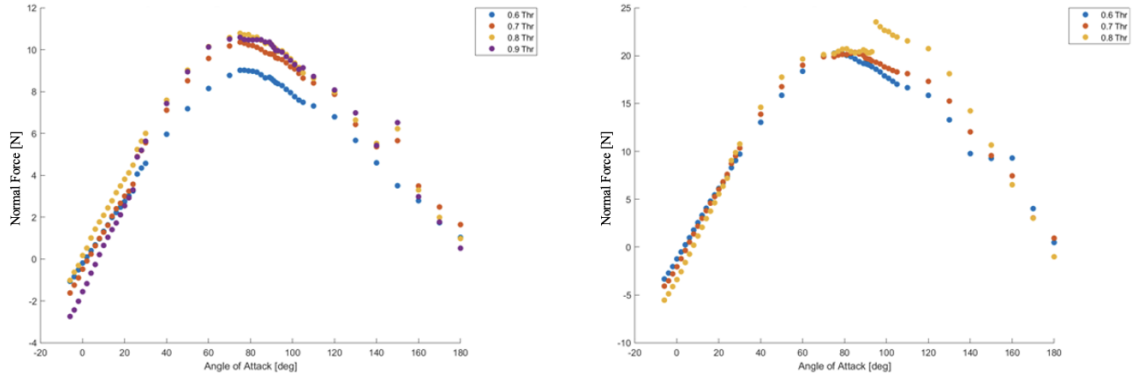


Figure 3.5: Normal Force: HST Fans at unusual angles DS82 and DS215, Thr on legend represents maximum RPM

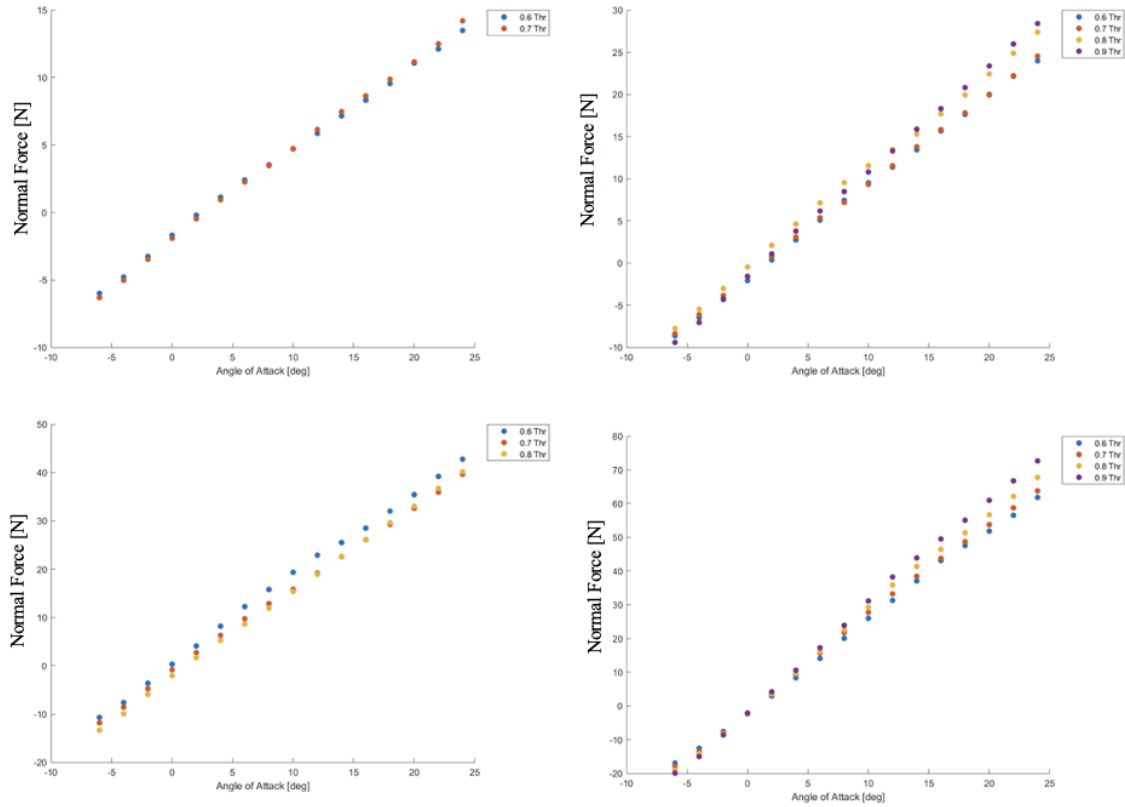


Figure 3.6: Normal Force: HST Fans at freestream velocity 40 m/s, Thr on legend represents maximum RPM

the stand configuration simulates the attachment of a conventional turbofan engine. This demonstrates that unexpected forces of a negligible nature could arise from an integration effect from the aircraft. For example, at 24 degrees angle of attack, the DS215's side force

at 0.8% throttle was 24% of the magnitude of the thrust.

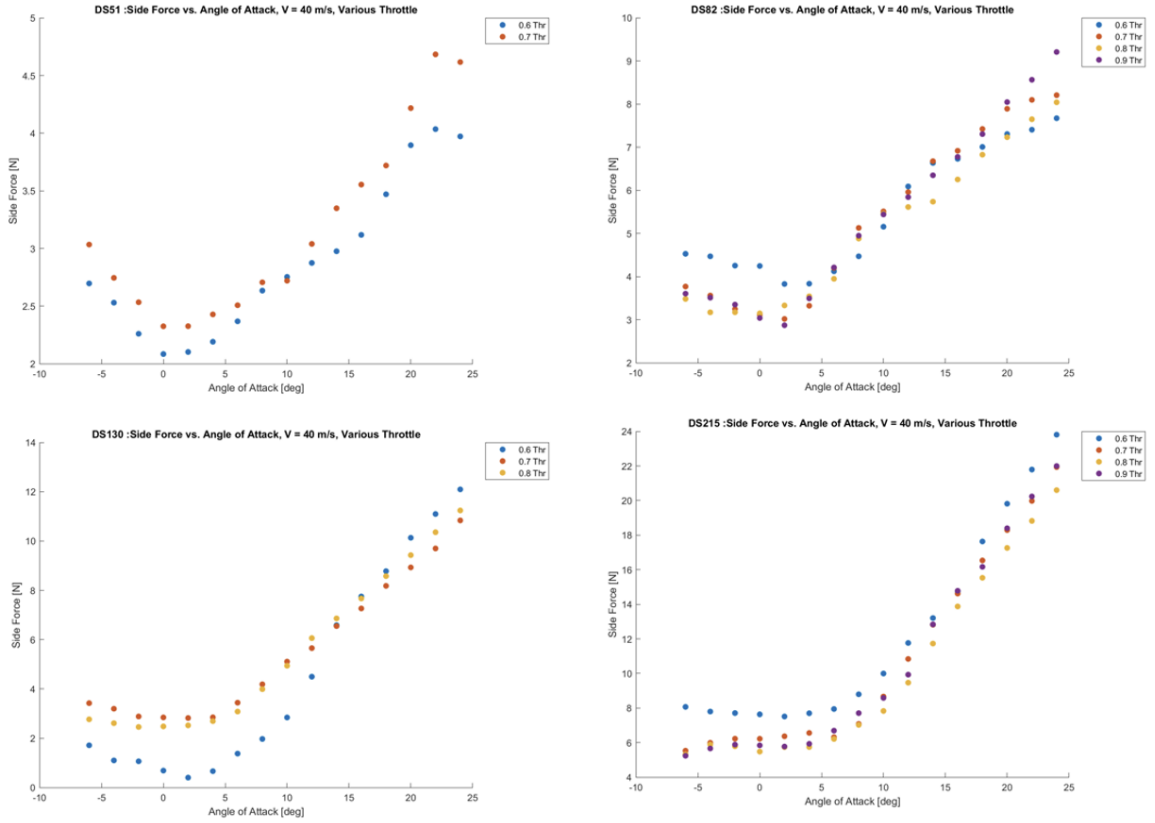


Figure 3.7: Side Force: HST Fans at freestream velocity 40 m/s, Thr on legend represents maximum RPM

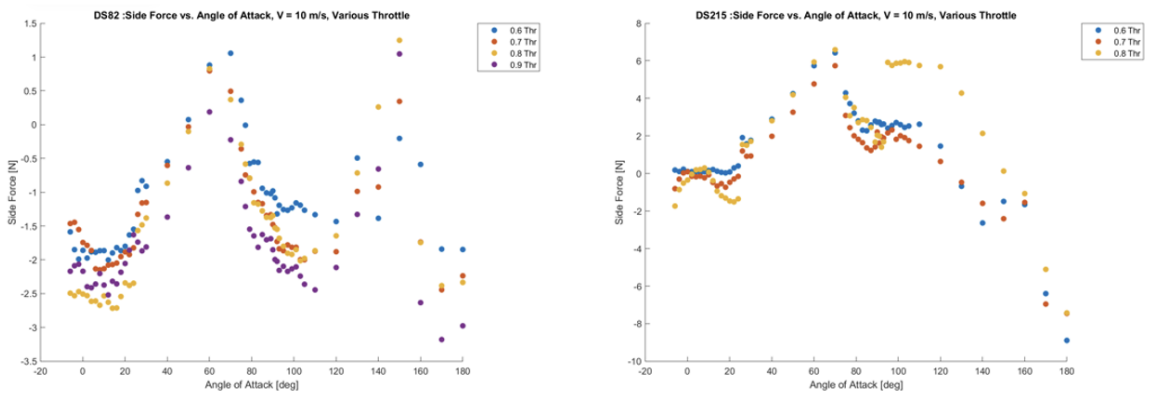


Figure 3.8: Side Force: HST Fans at unusual angles DS82 and DS215, Thr on legend represents maximum RPM

### 3.2.4 Pitching Moment

The transformed pitching moment represents the pitching moment with respect to the center of rotation and the origin of the rotor plane. The behavior observed is that the propulsor tends to have a destabilizing moment (away from the freestream velocity). This will be seen on the plots as a positive pitching moment for the negative angles of attack and a negative moment for the positive angles of attack.

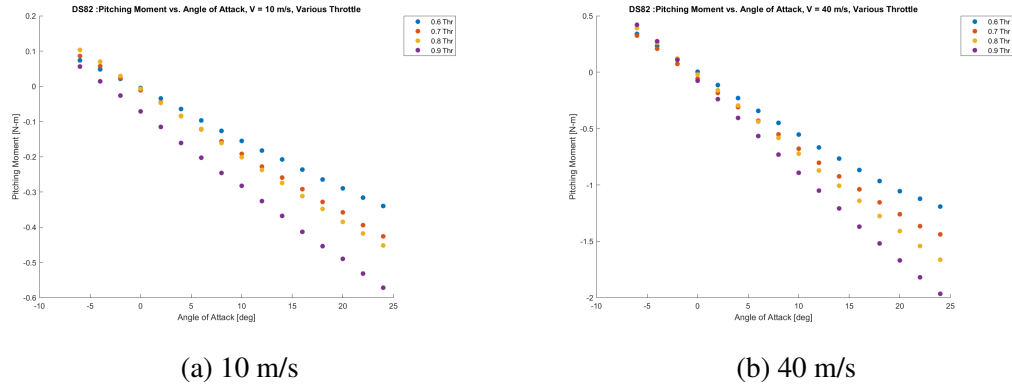


Figure 3.9: Pitching moment, DS82 airspeed comparison

Figure 3.9(a) shows the behavior at low airspeed, where the dominating factor is the rotor inflow velocity; for the case of the DS82, the effect is similar for the other sizes. The behavior is linear for the presented angles centered around 0 angle of attack; its slope depends on the thrust magnitude due to the lip thrust enhancement provided by the inflow velocity over the lip. At the higher angles of attack, the windward lip will produce more streamwise force, causing the thruster to turn from the wind. Figure 3.9(b) shows the regime where the freestream velocity dominates the behavior of the duct. In the plot, similar linear behavior is observed until the lip stalls. Compared with Figure 3.3, the spontaneous drop of thrust matches the angle where the pitching moment breaks its linear behavior. With the lip stalling, the thrust of the windward side of the lip loses thrust, hence its pitching moment generated. This explains why the thruster's tendency to pitch away from the freestream decreases when the lip stalls. In the case of the positive angles of attack, the moment turns

more positive (opposite behavior to when it's not stalled).

Figure 3.10 shows the pitching moment at all studied angles of attack. The destabilizing moment is the largest when the duct is in complete edgewise flight (90 degrees). This effect is mainly due to the dominance of the flow over the windward lip (the side of the inlet lip facing upstream). Figure 3.11 shows a smoke visualization done during the Clark-Y duct isolated tests that show the dominance of the flow over the windward inlet lip. In the image, most of the smoke seeding is ingested before reaching the other end of the inlet. The behavior is also in line with the simulations shown in Figure 3.31. Figure 3.12 shows the pitching moment for all the studied ducts at 40 m/s.

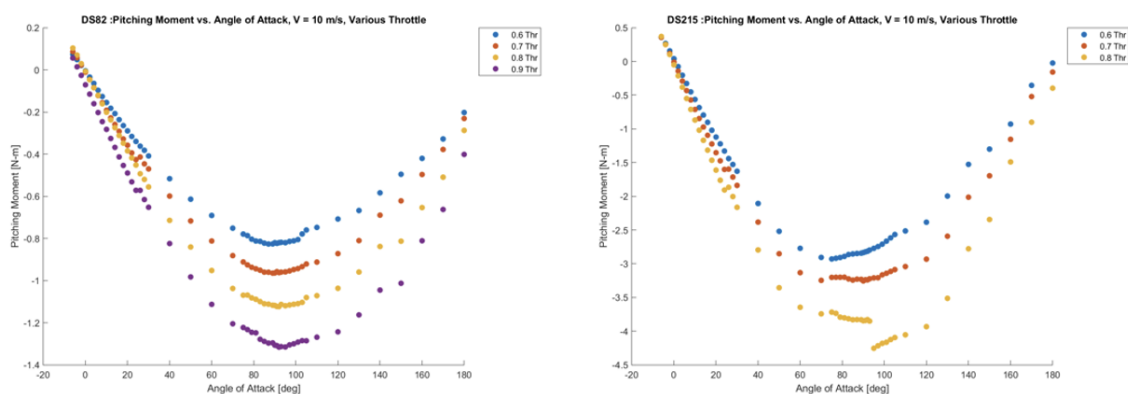


Figure 3.10: Pitching Moment: HST Fans at unusual angles DS82 and DS215, Thr on legend represents maximum RPM

### 3.2.5 Rolling Moment

The rolling moment of an EDF at cruise condition (0 degrees angle of attack) provides insight into the flow quality on the exhaust. Unlike a shrouded rotor, the EDF has a set of stator vanes that straighten the flow before it goes through the exhaust. Strong rolling moments in that flight regime could indicate over or under turning of the flow. All the EDFs studied were counterclockwise rotating fans; a negative rolling moment could indicate under-turning, and a positive moment could indicate overturning of the flow. The results in Figure 3.13 show that the DS51 straightens the flow properly as the moment

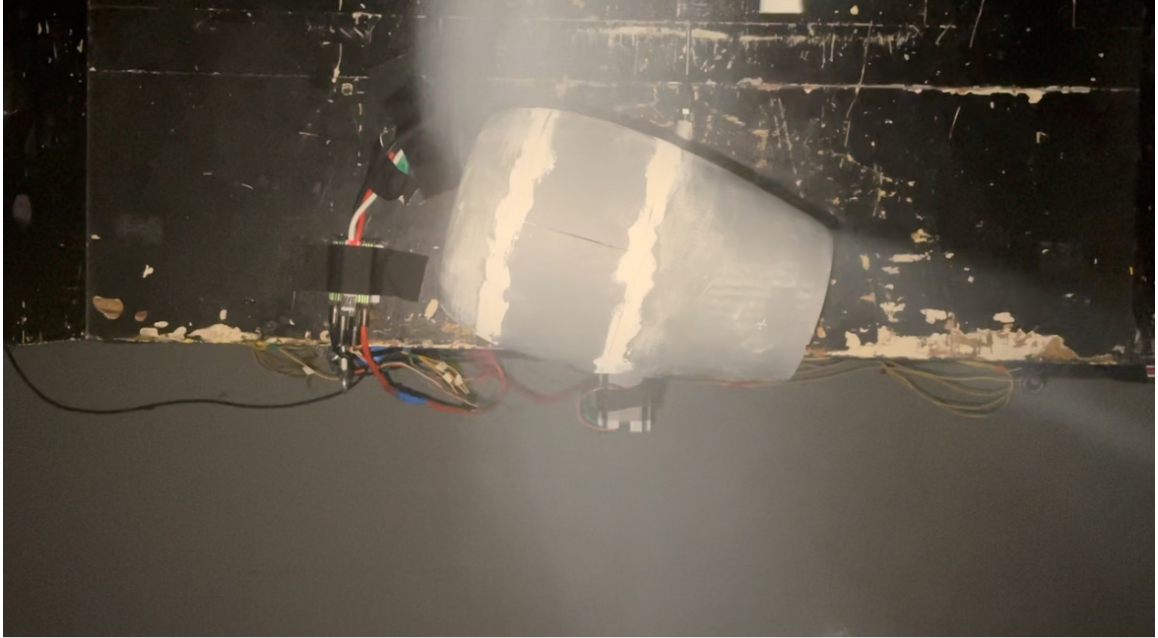


Figure 3.11: Smoke visualization from Duct Clark-Y testing showing the dominance of the flow over the windward inlet lip of a duct in edgewise flow.

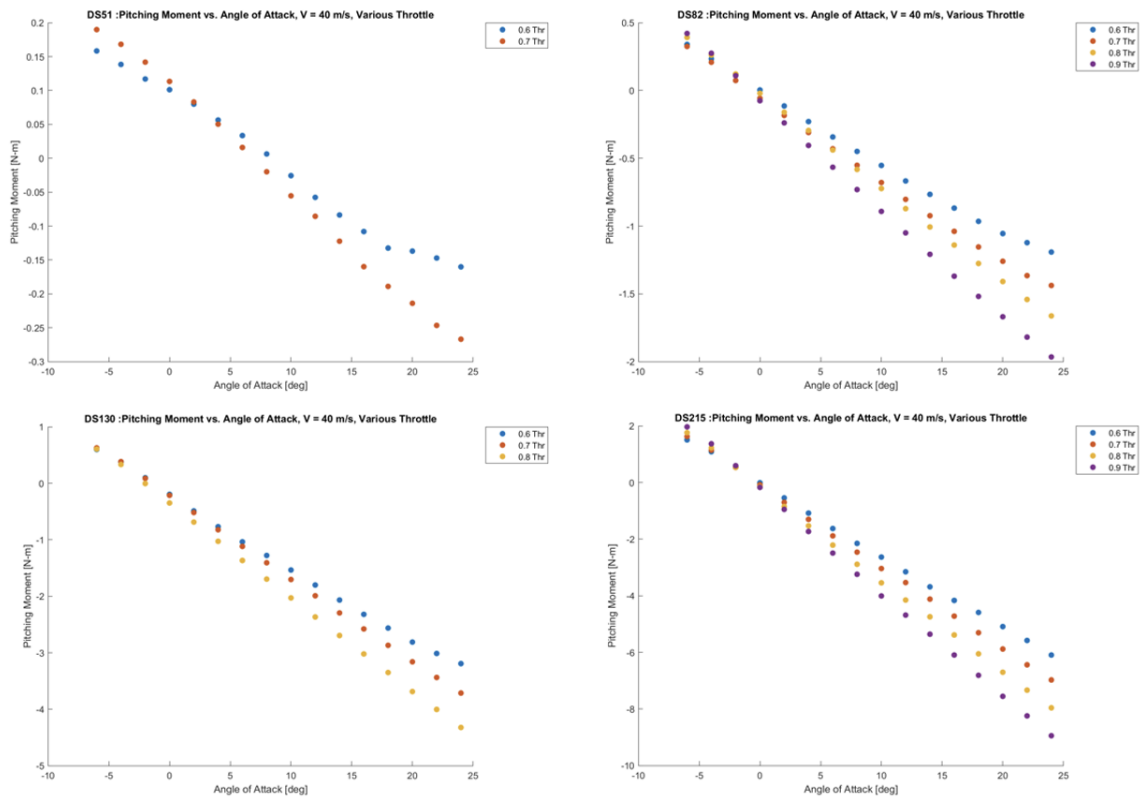


Figure 3.12: Pitching Moment: HST Fans at freestream velocity 40 m/s

is close to 0—the DS82 and DS130 show under-turning flow tendency while the DS215 shows overturning of the flow. The data shows that the fan stators provide the right amount of turning at a throttle percentage of 60% as they approach 0 N-m rolling moment in the cruise conditions.

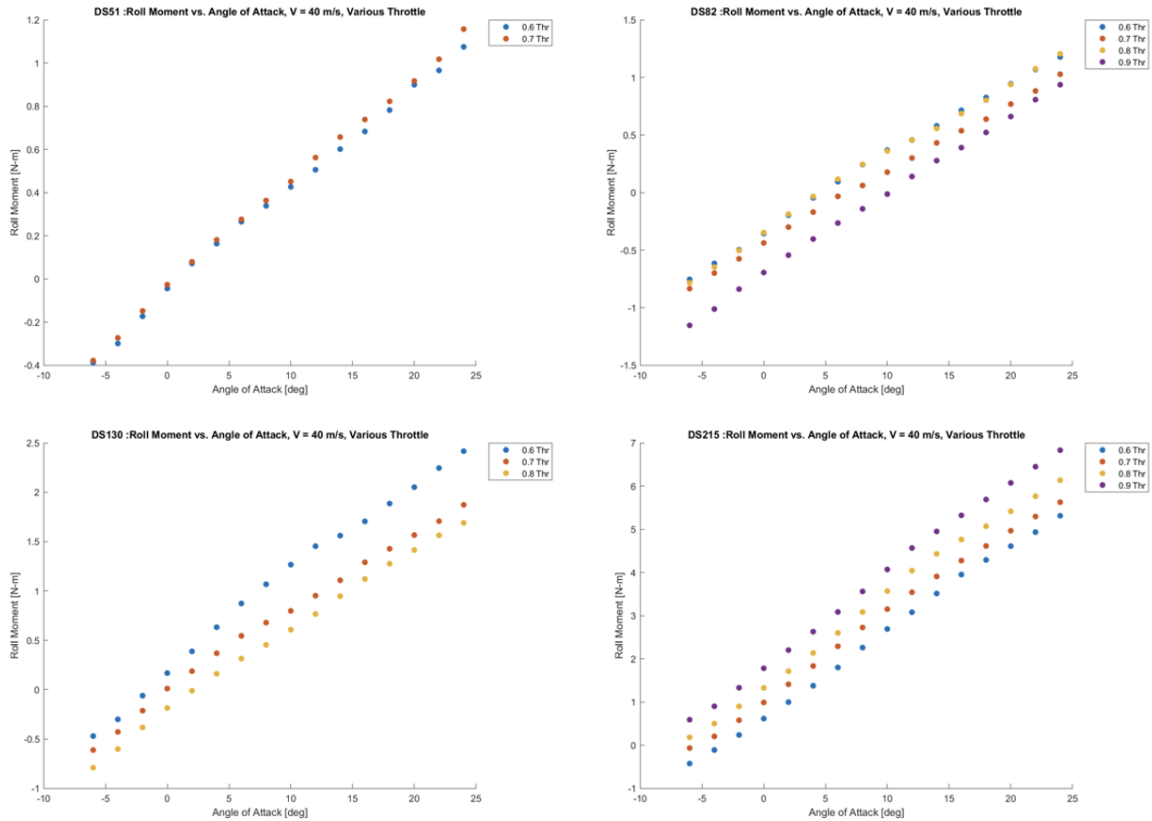


Figure 3.13: Rolling Moment: HST Fans at freestream velocity 40 m/s, Thr on legend represents maximum RPM

### 3.2.6 Yawing Moment

The yaw moment for the EDFs is shown in Figure 3.15; similar to the other measurements, its behavior is mandated by which airflow has dominance. This moment and the side force measurement are the most contaminated by the rig, especially by the loadcell placement. In this case, the yawing moment is shown at the origin of the loadcell. This was done to show the EDF affects the system it is mounted on. While external factors might generate these

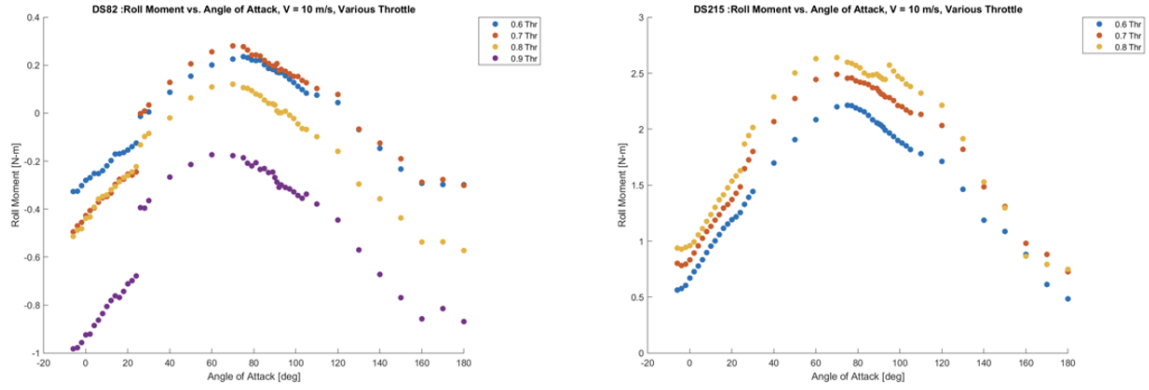


Figure 3.14: Rolling Moment: HST Fans at unusual angles DS82 and DS215, Thr on legend represents maximum RPM

trends, it is important to note that they mimic integrations commonly found on aircraft.

Figure 3.16 presents the yaw moment for the unusual attitudes.

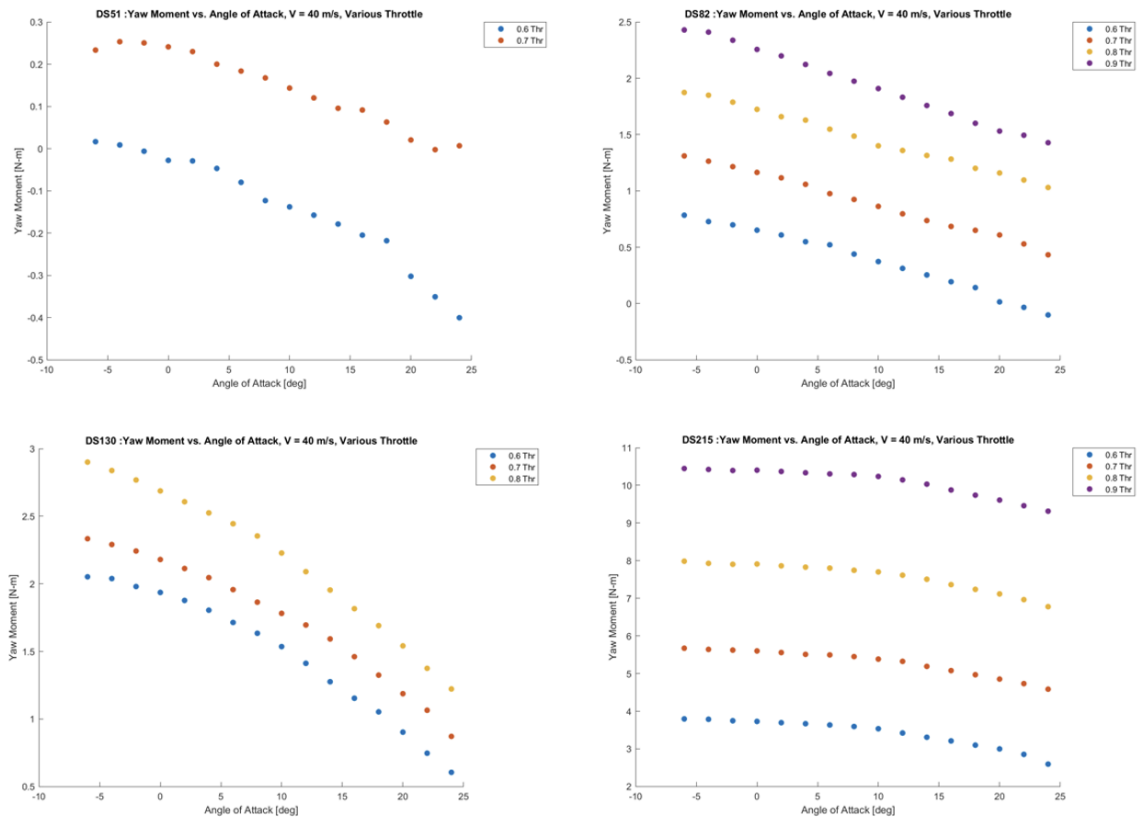


Figure 3.15: Yawing Moment: HST Fans at freestream velocity 40 m/s, Thr on legend represents maximum RPM



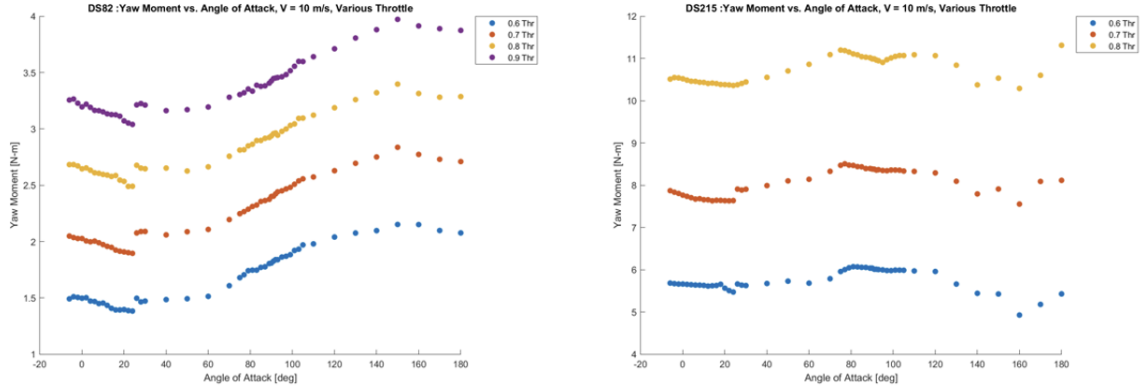


Figure 3.16: Yaw Moment: HST Fans at unusual angles DS82 and DS215, Thr on legend represents maximum RPM

### 3.2.7 Inlet Pressures

The inlet pressures on the windward lip of the duct are studied in this subsection. Representative plots are shown to investigate the effects of lip stall and velocity enhancement over the windward lip. The effects of inlet stall are best observed in Figure 3.18 where the windward lip stalls at around 20 deg. The furthest angle shown in Figure 3.18 starts showing higher irregularity in the pressure, denoted by a larger error bar. Another interesting point is that the stagnation point at the inlet (marked by the transition from a positive pressure to a negative) moves further into the duct in all pressure figures. In some cases, the transition occurs up to port 3, which is 17% of the inlet length.

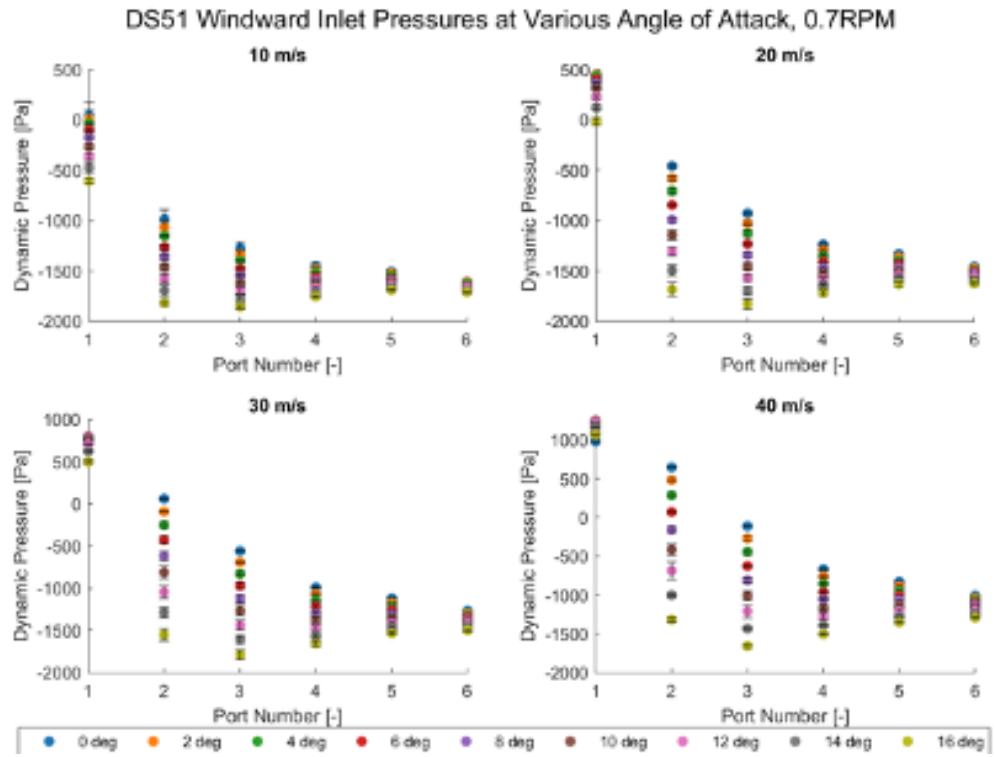


Figure 3.17: Inlet Pressures: DS51

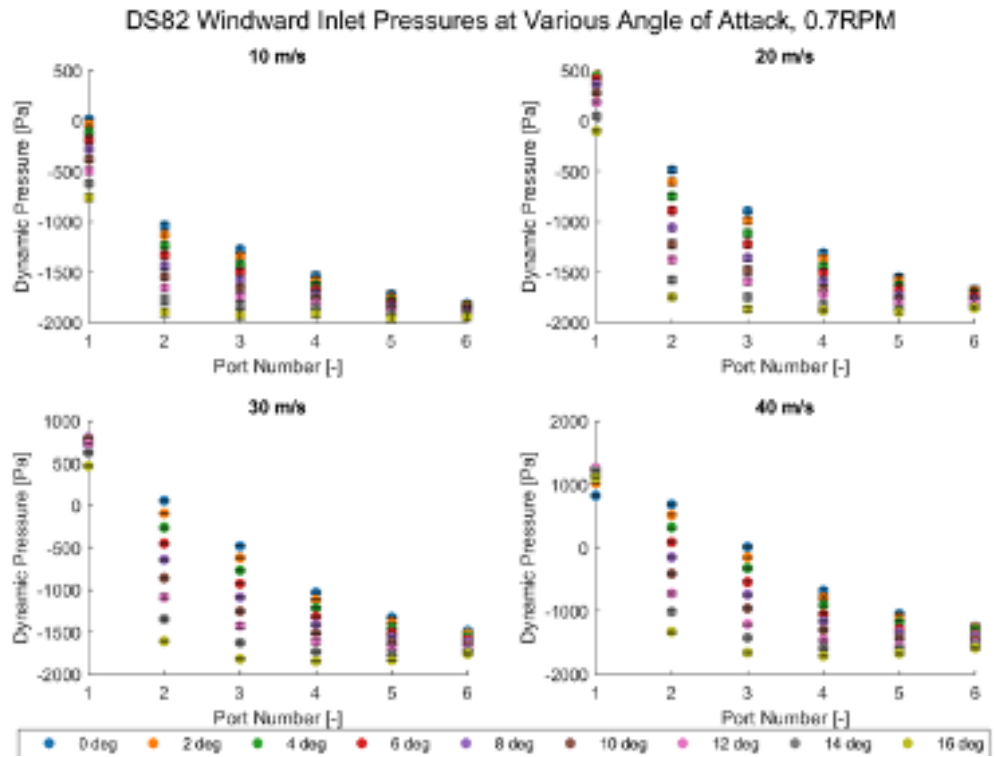


Figure 3.18: Inlet Pressures: DS82

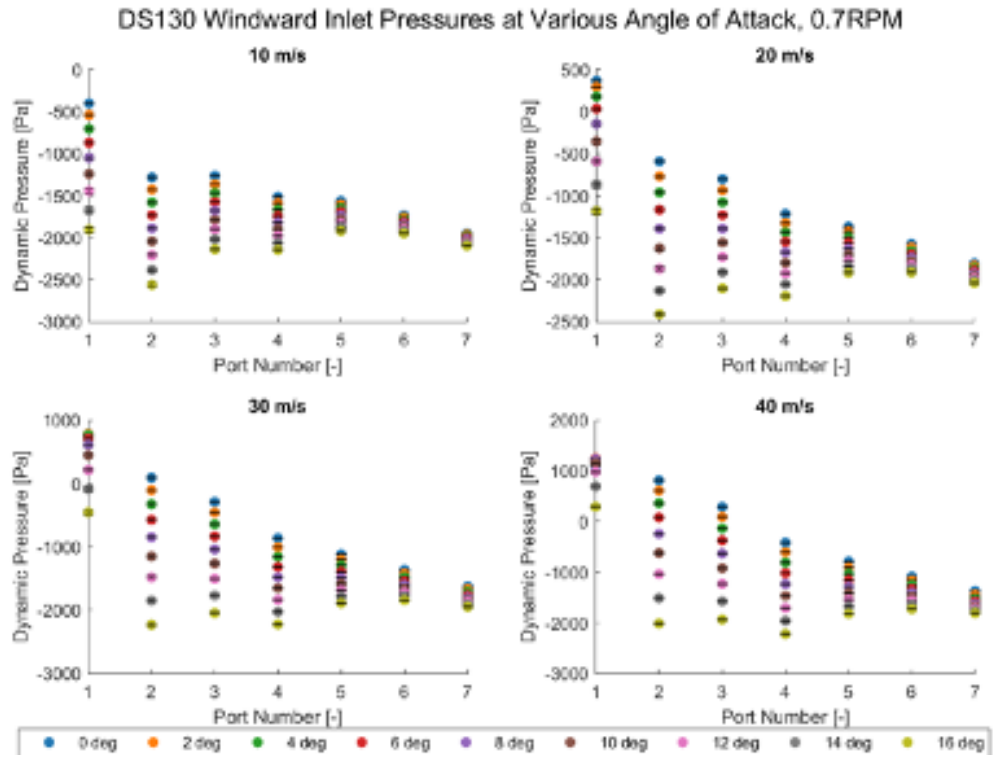


Figure 3.19: Inlet Pressures: DS130

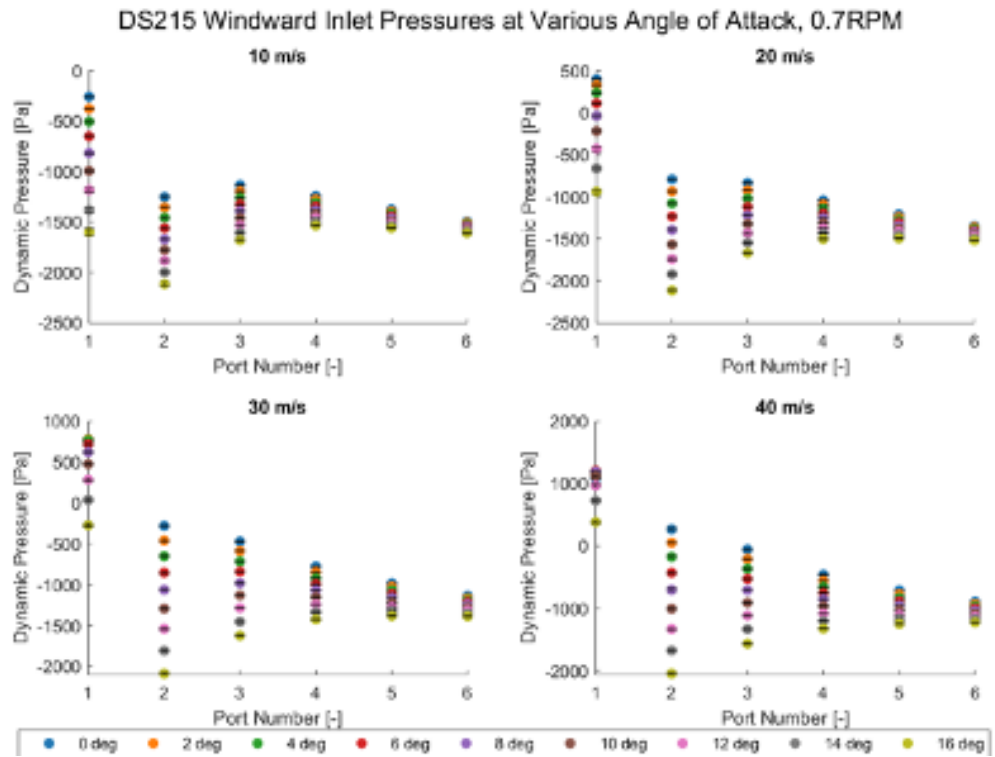


Figure 3.20: Inlet Pressures: DS215

### 3.2.8 Exhaust Pressure Profile

Observing the data from the wake rake to study the exhaust of the thruster can provide further insight into the thruster's performance. Note that the center port represents the center of the thruster, and it is blocked by the center body. The ports with a higher number than the middle are found on the windward side, and the ones marked with less than the middle are the ports located on the leeward side of the duct. Figure 3.21 - Figure 3.24 show the exhaust pressures for various airspeeds and angles of attack.

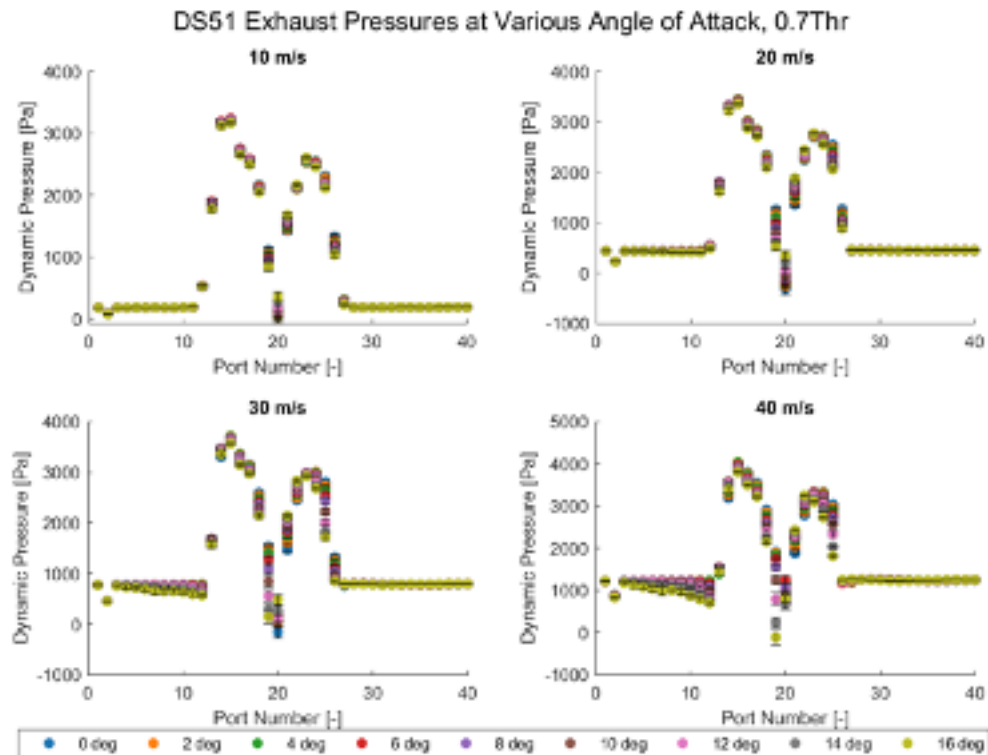


Figure 3.21: Exhaust Pressures: DS51

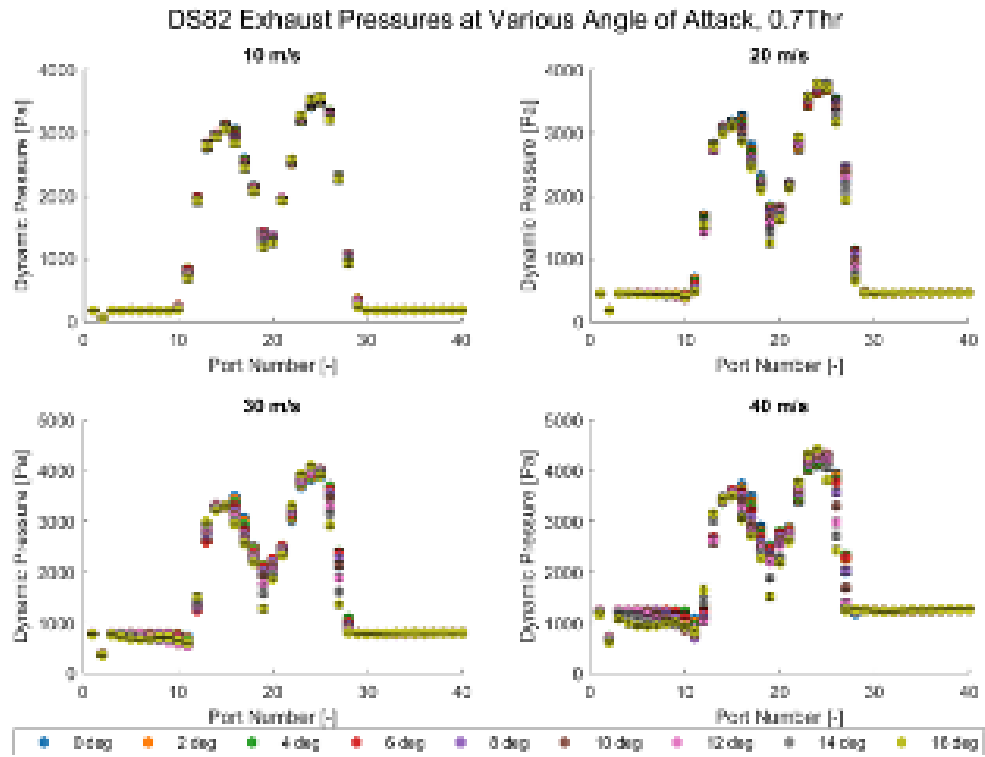


Figure 3.22: Exhaust Pressures: DS82

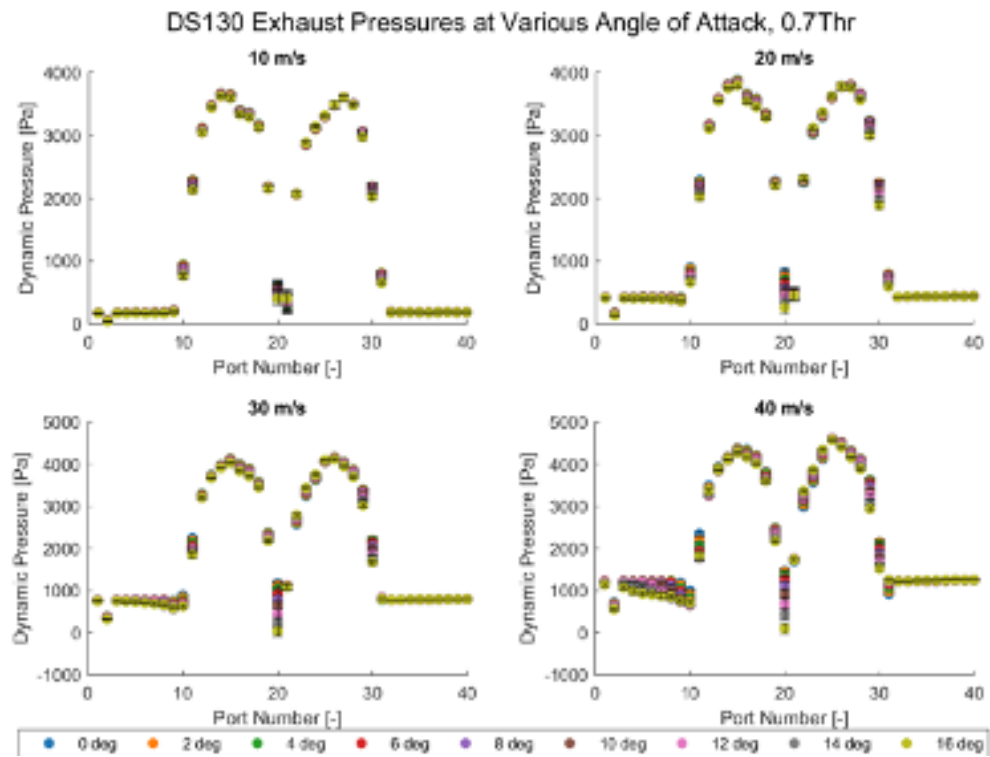


Figure 3.23: Exhaust Pressures: DS130

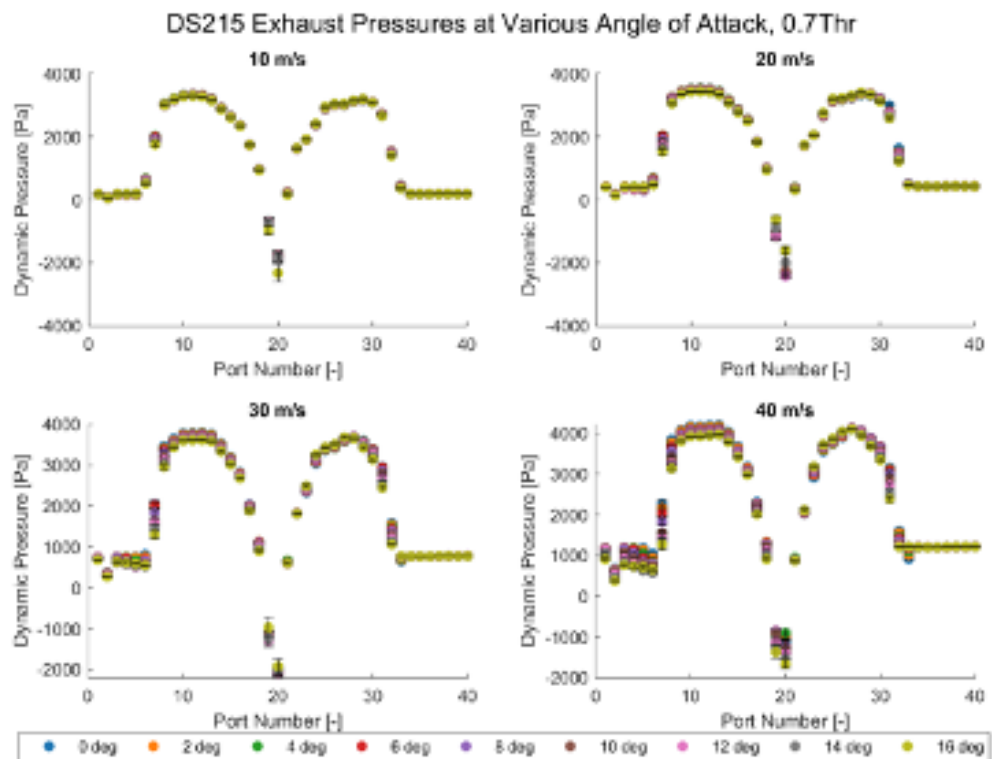


Figure 3.24: Exhaust Pressures: DS215

### 3.2.9 Performance Comparison

For performance, the metrics used are overall efficiency, propulsive efficiency, and power loading. The definitions of these are described by Equation 3.2, Equation 3.3, and Equation 3.4. In these cases,  $T$  is thrust generated,  $V_{\text{inf}}$  is the freestream velocity,  $V_{\text{meanjet}}$  is the average jet exhaust velocity,  $P_{DC}$  is the DC power.

$$\eta_{\text{overall}} = TV_{\text{inf}}/P_{DC} \quad (3.2)$$

$$\eta_{\text{propulsive}} = 2/(1 + (V_{\text{meanjet}}/V_{\text{inf}})) \quad (3.3)$$

$$\text{Power Loading}(PL) = T/P_{DC} \quad (3.4)$$

In rotorcraft literature, power loading is used as a performance metric to compare rotors of different sizes and disk loadings. This metric will be used to compare the various EDF sizes studied because it is a global performance metric that does not rely on assumptions. In this case, Power is defined as the electric DC power required, not the mechanical shaft power.

Figure 3.25 - Figure 3.27 show the various performance metrics comparing the HST fans. More specific observations relate to the size of the EDFs. Figure 3.25 shows that the overall efficiency of the EDFs increases with size and provides higher efficiency at a broader range of advance ratios. The propulsive efficiency is shown in Figure 3.26 shows the opposite trends, with the smaller size EDFs with a larger efficiency. This is attributed to the higher jet exhaust speeds that the smaller EDFs have. For example, the jet exhaust speed of the DS51 is 11.5% greater than the DS215.

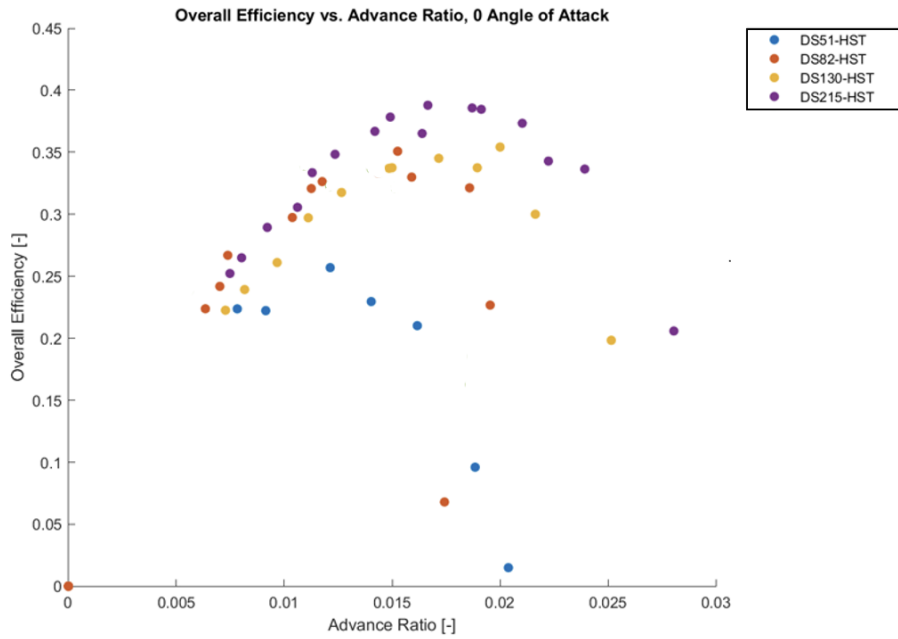


Figure 3.25: Overall Efficiency: HST Fans calculated with Equation 3.2

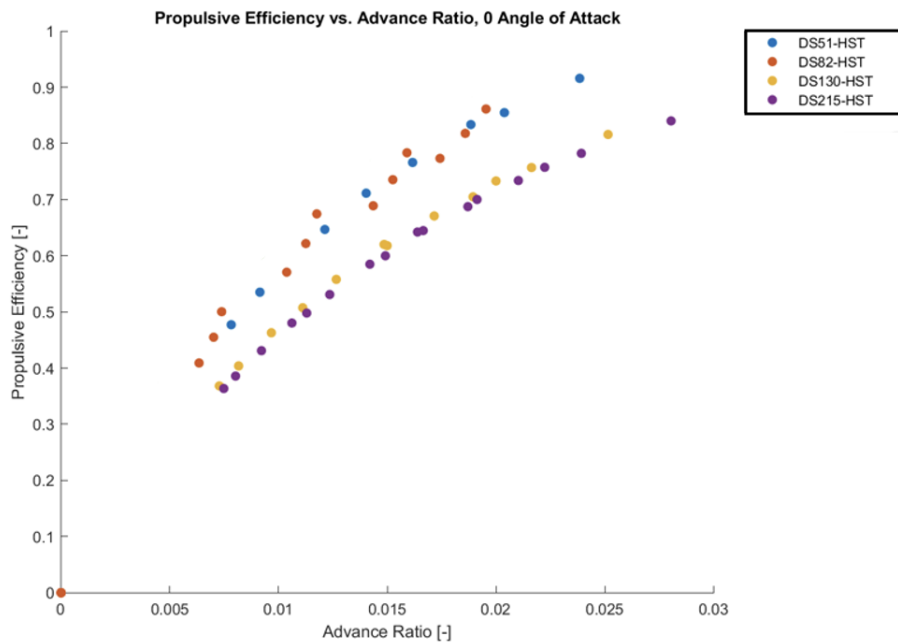


Figure 3.26: Propulsive Efficiency: HST Fans calculated with Equation 3.3



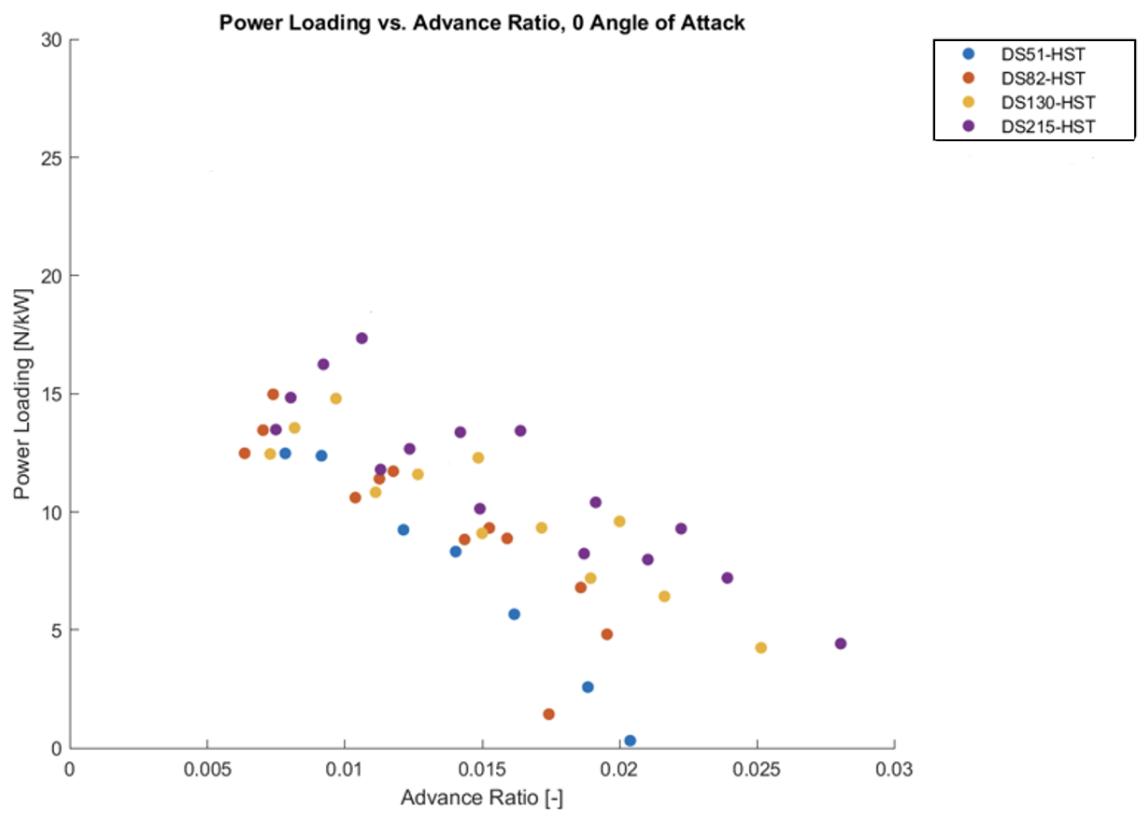


Figure 3.27: Power Loading: HST Fans calculated with Equation 3.4

### 3.2.10 PIV Results

The goal of the PIV campaign was to prove that the lab could do PIV up to the rotor plane of an EDF. The difficulties encountered and preliminary results are discussed. The first and most significant one is the spinning fan blades in the background that introduced highly unsteady reflections that reduced image quality. This also caused vector calculation to be more challenging since there were movements of the particles and the fan blades, which can be difficult to differentiate through processing. Depending on the level of reflection off the blades, this could result in entirely incorrect vector fields. The other challenge was the confined space inside the duct inlet where reflections off the duct and the fan, even with them all painted black, illuminated everything around and significantly reduced the signal-to-noise ratio. To overcome these first two challenges, better surface treatment to minimize reflections and more advanced image filtering techniques might be necessary. The last challenge was the significant difference in velocities within the ROI (Region of Interest) at higher throttle settings and lower freestream velocities. In these conditions, the pulse separation time and the interrogation window must be carefully chosen such that the movement of the particles between frames moves an appropriate number of pixels across the entire AOI for good cross-correlations and, hence, more accurate velocity vector maps.

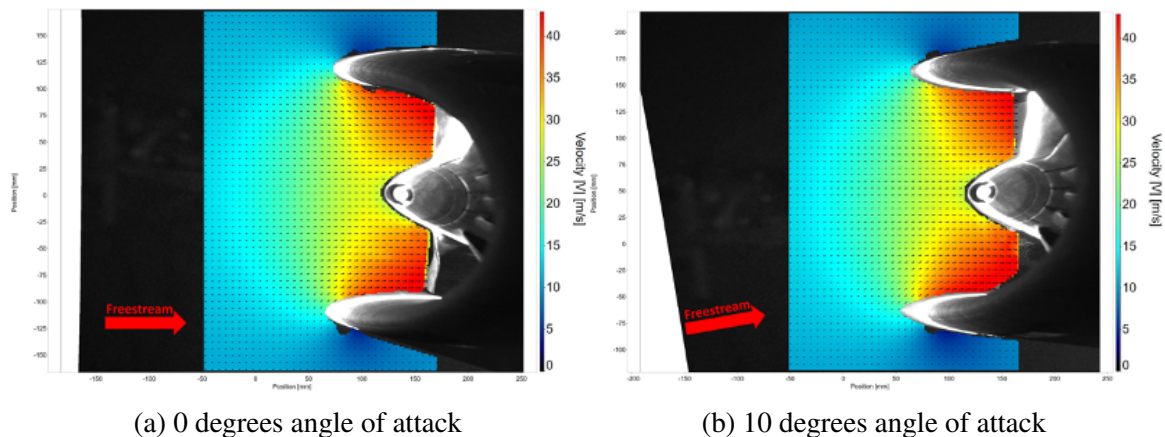


Figure 3.28: Time-averaged velocity magnitude overlaid on the raw image of DS215-HST at 8500 RPM at 10 m/s freestream (only every 4th vector is shown)

Even though there were some complications in creating a comprehensive data set, some good time-averaged velocity fields were produced. Figure 3.28 shows the velocity profile up to the rotor plane of the DS215-HST EDF. The expected, somewhat triangular trend with higher velocity at the blade tips and a reduced velocity towards the hub is observed. The average velocity at the rotor plane matches within 5% with the expected induced velocity from momentum theory (extracted from thrust). The asymmetry on the velocity field is also observed in Figure 3.28(b) with a higher velocity profile on the windward lip of the inlet.

### 3.3 Isolated EDF (Clark-Y Duct) Baseline

An initial testing campaign was conducted at Georgia Tech's 1 m x 1 m Low Turbulence Wind Tunnel to validate the self-rotating test rig and obtain the baseline data for the studied EDF. The results are divided into two sections: the forces and the moments.

#### 3.3.1 Propulsive Force (Thrust) Discussion

The most important force studied for this test was the propulsive force, defined as the combination of rotor thrust and the propulsive contribution of the duct. This force is defined in the rotor plane, meaning that it will always be perpendicular to the rotor and independent of the angle of attack of the duct. Following the rotorcraft convention, the non-dimensionalization was done by dividing the force value by  $\rho A_{rotor} V_{tip}^2$ . Figure Figure 3.29 presents the thrust data obtained at different throttle conditions.

As is expected, across all conditions, the static thrust presents a linear behavior; the asymmetry seen is attributed to facility effects that are currently being quantified. As the freestream velocity increases, thrust reduction is observed when the duct aligns perpendicularly with the freestream flow. This phenomenon occurs because the freestream component normal to the rotor plane is a function of the cosine of the angle of attack relative to the rotor plane, meaning its maximum value will occur at 0. Physically, the overall induced velocity in the rotor plane is dependent on the normal freestream component; hence at lower

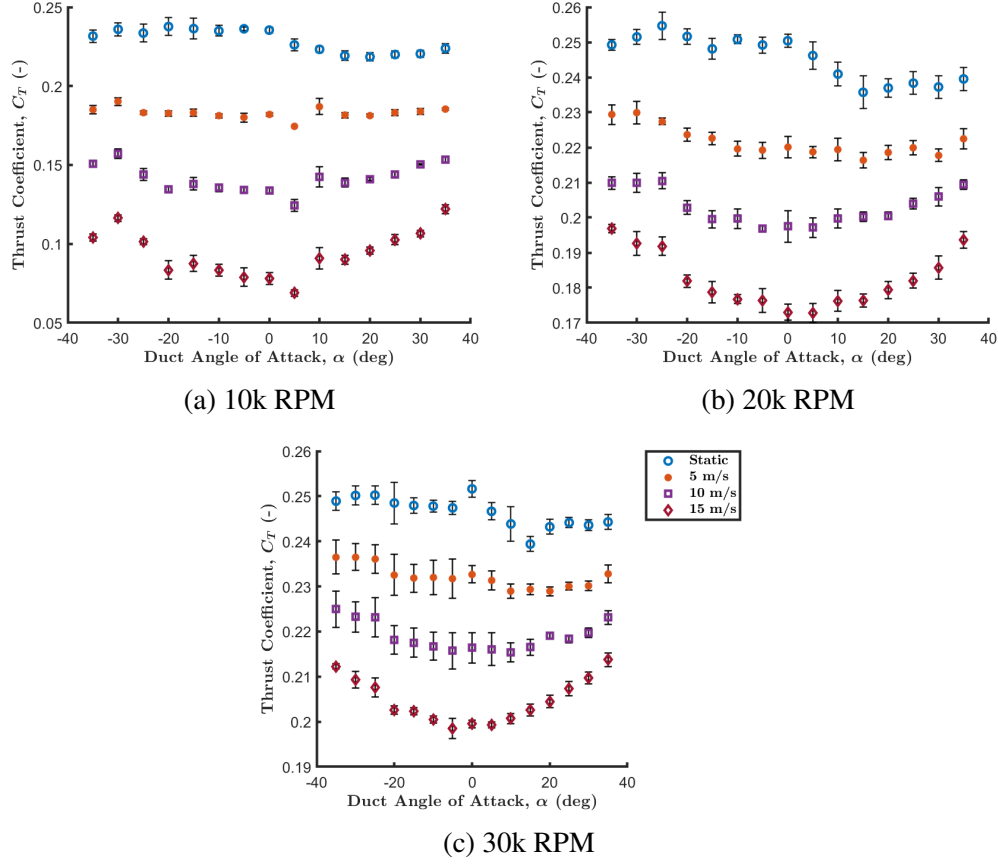


Figure 3.29: Thrust Coefficient vs. Angle of Attack for Various RPM Conditions

angles of attack the inflow will be the largest, leading to a reduction of the local angle of attack of the blade, ultimately causing the thrust reduction.

### 3.3.2 Pitching Moment Discussion

Understanding moments being generated by the ducted fan and then transmitted to the vehicle is of extreme importance as these phenomena could outweigh the benefits of blended wing-propulsor configurations. This part of the results focuses on discussing the pitching moment generated by the system at different angles of attack. Figure Figure 3.30 shows the pitching moment generated by the EDF. The pitching moment is attributed to a thrust imbalance in the rotor plane and a pitching moment generated by the duct due to the accelerated flow on the lip leading the movement. This effect is similar to the pitching-up

moment observed by Yaggy when studying a wing-tip-mounted ducted fan during the transition [12]. FlightStream was then used to explore the change in velocity profile at the rotor plane to understand the thrust imbalance portion of the moment observed. The results are seen in Figure Figure 3.31. It is observed that the rotor side that is windward (bottom section of the rotor plane) has higher overall inflow speeds than the leeward side, the maximum value seen was 9.7 m/s which represents 6.7% of the tip speed for that condition. This correlates to a decrease of 3 degrees of the blade local angle of attack in the windward side of the duct with respect to the leeward side. This phenomenon is generated by an acceleration in the lip of the duct and causes the observed flow asymmetry. The change of angle of attack creates a restoring moment on the rotor, causing a pitching moment to move towards the wind. This also uncovers the existence of a high-frequency oscillatory load that could have detrimental effects on the blade as EDF blades are usually stiff and transfer all their moment to the hub. On the other hand, the acceleration over the lip causes the windward lip of the inlet to generate more thrust, causing a pitching moment away from the wind. This data will serve as a baseline to compare the differences in integration as this contribution cannot be assumed negligible, especially for VTOL configurations that will cycle through flight transitions every hour.

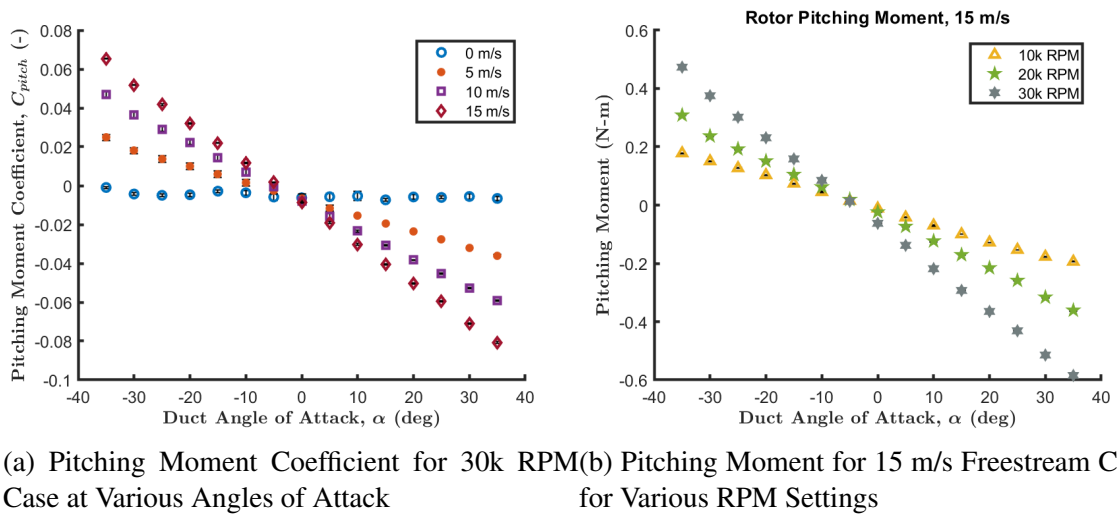


Figure 3.30: Pitching moment study for various testing conditions

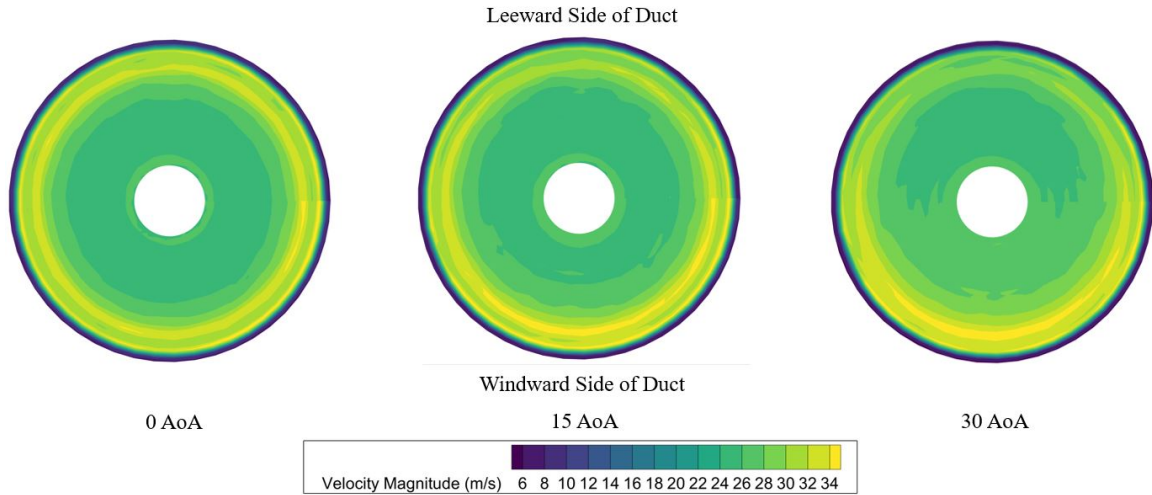


Figure 3.31: Rotor inflow velocity magnitude for various angles of attack at 30k RPM and 15 m/s Freestream

### 3.4 Symmetrical Airfoil Integrated EDF

This section is divided by measurement type. The most important measurements that are discussed are the thrust coefficient measurement and pitching moment at the rotor plane. The power loading is analyzed as the overarching performance metric. Lastly, high-frequency and acoustic measurements' results are discussed through a short-time Fourier transform (STFT).

All measurements discussed in this section have been transformed to be relative to the rotor plane and axis of rotation. The plots shown in the section are representative of the test matrix and were chosen to showcase repeatable trends observed during the testing campaign. Error bars represent one standard deviation of the average of the independent tests.

#### 3.4.1 Thrust Coefficient

The thrust coefficient is preferred to the dimensional thrust for analysis to account for various environmental conditions observed for different testing days. The rotorcraft convention was selected for non-dimensionalization. Note that the thrust force includes both the rotor

and duct forces.

### Leading Edge Integration

Figure 3.32 shows the thrust coefficient with respect to the angle of attack for various RPM cases for the leading edge integration. The isolated duct thrust coefficients are shown with lines, while the integrated thrust coefficients are shown with markers. The integrated EDF exhibits a similar behavior as the isolated EDF for all cases at 5 m/s, as shown in Figure 3.32(a). When the freestream velocity is increased to 10 m/s, the integrated EDF behavior deviates from the isolated EDF ( Figure 3.32(b)). At higher advance ratios (lower RPM for same airspeed), the minimum thrust coefficient angle of attack shifts towards the positive angles of attack (a pitch-down angle for this reference). For both the upper and lower integration cases, the isolated EDF produces more thrust than the integrated version, except for the 15k RPM at 10 m/s, for which the minimum thrust has a similar magnitude.

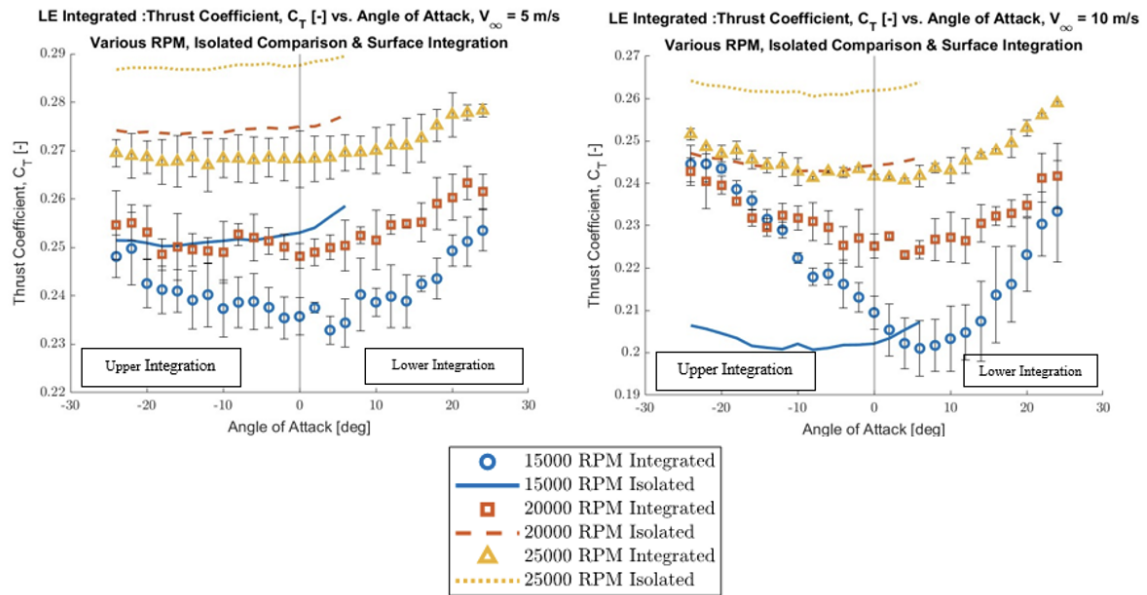


Figure 3.32: Thrust coefficient for leading edge integration at various conditions compared to isolated EDF for both surface integrations. Top figure at 5 m/s and bottom at 10 m/s

### Trailing Edge Integration

Figure 3.33 shows the thrust coefficient vs. angle of attack for various RPM cases for the trailing edge integration and the isolated EDF. As observed for the leading edge integration cases, the integrated EDF produces less thrust coefficient than the isolated EDF. This can be attributed to the increased local flow speed generated by the wing. This effect is shown in Figure 3.33(b), where the upper surface integration (negative angles of attack) produces less thrust coefficient due to higher local airspeeds. The effect is most notable for the high RPM case because the higher inflow velocities generated by the higher RPM delays separation over the wing and further increases its local velocity. Note the increased unsteadiness of the measurements for the upper integration at higher freestream velocities. This is attributed to the increased unsteadiness of the wing's boundary layer as it approaches a separation state. For the lower airspeed cases, the rotor inflow velocity dominates the flow field and controls separation in the measured cases.

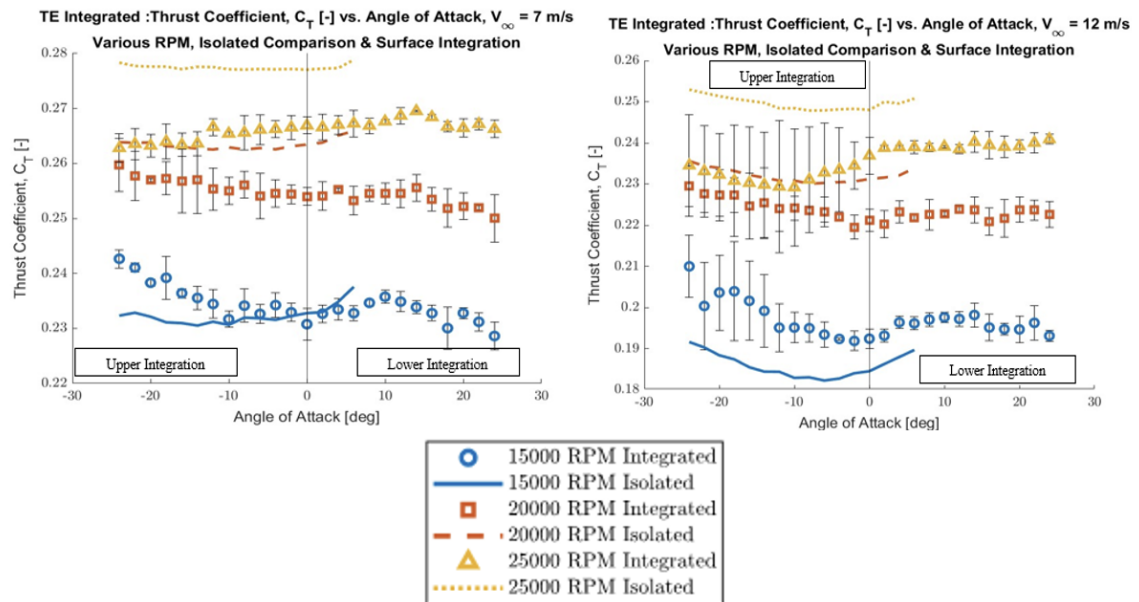


Figure 3.33: Thrust coefficient for trailing edge integration at various conditions compared to isolated EDF for both surface integrations. Top figure at 7 m/s and bottom at 10 m/s



### 3.4.2 Pitching Moment, $M_Y$

The pitching moment is presented in its dimensional form. For the EDF loads, pitching moment is a combination of the rotor pitching moment due to asymmetric inflow and the imbalance of the inlet thrust forces. The rotorcraft non-dimensionalization did not show useful trends to characterize the behaviour.

The isolated EDF data ( Figure 3.34) shows the dominance of the inlet forces on the generation of pitching moment. For rotors, the moment observed at the rotor plane is expected to be a restoring moment towards the 0 angle of attack condition. The flow accelerates over the inlet lip (if not separated), causing higher inflow velocities on the windward side of the duct. This effect causes lower thrust on the rotor disk's windward side, generating a stabilizing moment due to thrust imbalance. The inlet, on the other hand, produces a destabilizing moment. The windward side of the inlet produces more streamwise force than the leeward. In addition, the leeward side of the duct acts more as an airfoil, hence creating a large tangential force that aids the destabilizing behavior. Figure 3.34 shows the dominance of the destabilizing moment over the rotor generated stabilizing moment. The behavior can be seen at the higher angles where the pitching moment is positive.

#### *Leading Edge Integration*

Figure 3.34 shows that the leading edge integration exhibited similar behavior as the isolated EDF for the upper integration. That behavior is expected as the duct is in a similar configuration as the isolated. In the case of the lower integration, the behavior is mostly constant. The leeward side of the duct is integrated into the wing, reducing the produced tangential force to zero, and the inlet destabilizing moment reduces to only the streamwise force imbalance. This behavior is replicated for all airspeeds and RPM. The destabilizing and stabilizing moments must increase at similar rates to create the angle independent destabilizing moment.

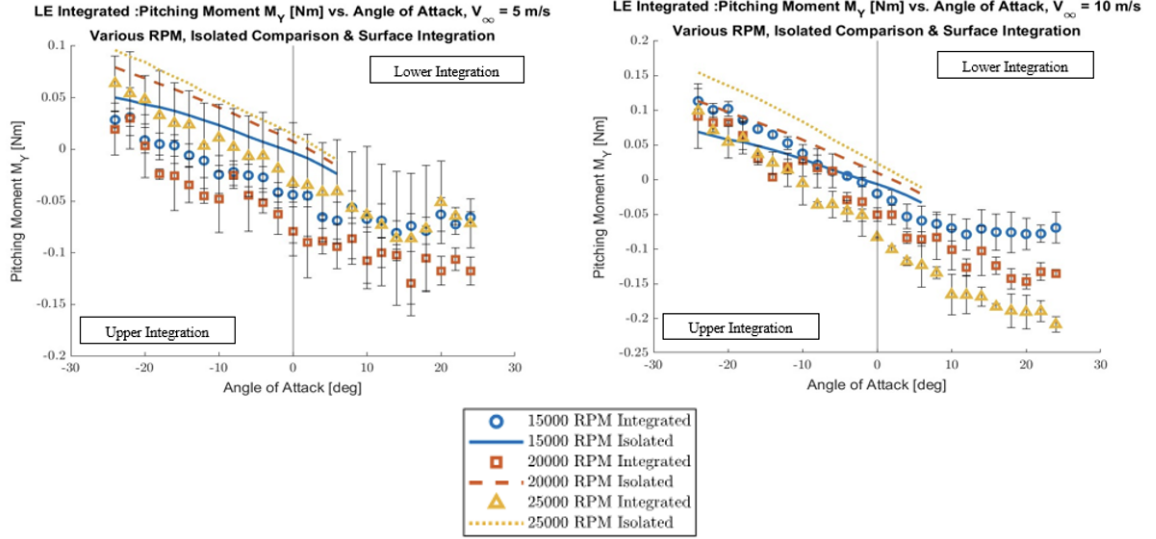


Figure 3.34: Pitching moment for leading edge integration at various conditions compared to isolated EDF for both surface integrations. Top figure at 5 m/s and bottom at 10 m/s

### Trailing Edge Integration

Figure 3.35 shows the pitching moment with respect to the angle of attack for the trailing edge integrated EDF. The results show a pitching down moment across all the studied angles. From a rotor forces perspective, the side of the duct ingesting the boundary layer (BL) would cause higher thrust, hence a positive moment. The experimental results shown in Figure 3.35 give insight into the dominance of the duct forces for these testing conditions: the side of the inlet attached to the wing's surface is not producing any streamwise force while the one on the freestream does, generating a dominating force imbalance that leads to the observed behavior.

### 3.4.3 DC Power Required

The power required is presented as a dimensional magnitude, although the percentage differences between dimensional and non-dimensional remain the same.

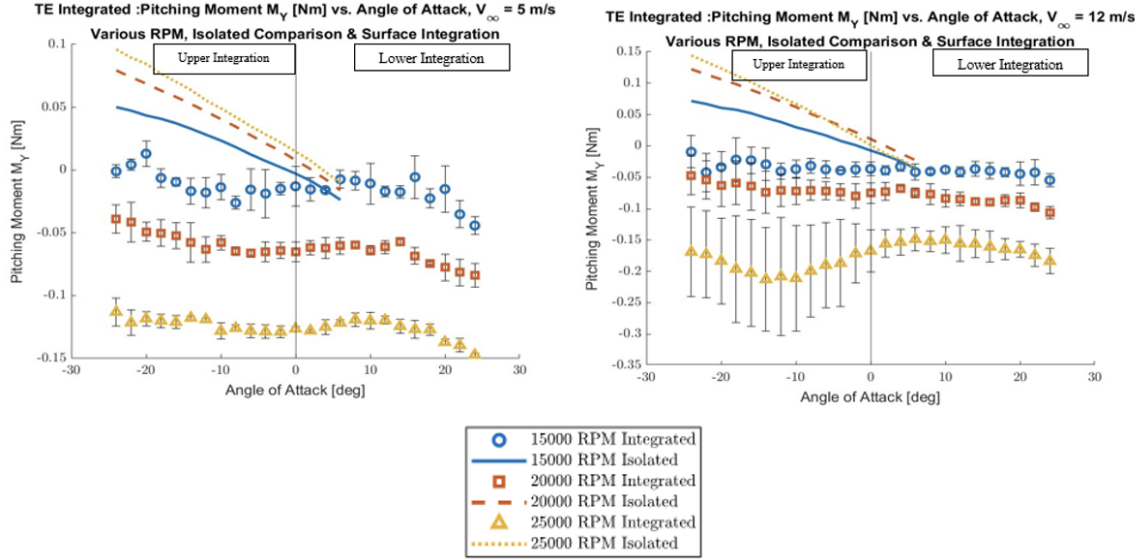


Figure 3.35: Pitching moment for trailing edge integration at various conditions compared to isolated EDF for both surface integrations. Top figure at 5 m/s and bottom at 12 m/s

### Leading Edge Integration

Figure 3.36 shows the power required at 12 m/s at various RPMs for the leading edge integration. The overall power required was less for the integrated version than for the isolated EDF. This could be attributed to the acceleration of the flow caused by the presence of the wing. Similar to what was observed in the performance trends, the percentage difference between the isolated and the integrated version was a function of the advance ratio. More power required benefit was observed for the lower RPM (higher advance ratio). For the 12 m/s case, the average power required benefit for the 25k RPM case was 5%, 20k RPM 5%, and 15k RPM was 8%.

### Trailing Edge Integration

Figure 3.37 shows the power required at 12 m/s at various RPM for the trailing edge case. The trends are similar to the ones for the leading edge case, and are therefore not described for brevity. In this case, the average power required benefit for the integration was 7% for the 25k RPM, 9% for 20k RPM, and 12% for 15k RPM.

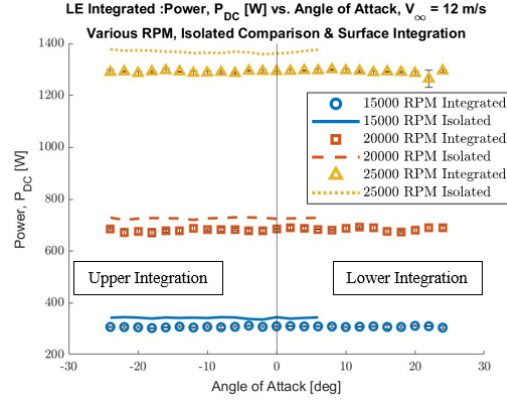


Figure 3.36: DC power required for leading edge integration at various conditions compared to isolated EDF for both surface integrations at 12 m/s

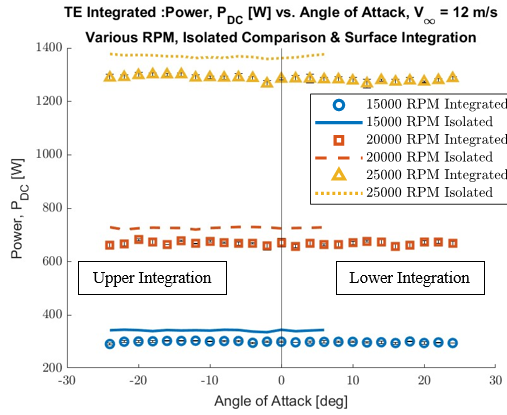


Figure 3.37: DC power required for trailing edge integration at various conditions compared to isolated EDF for both surface integrations at 12 m/s

### 3.4.4 Performance Analysis

The performance metric used in this study was the non-dimensional power loading ( $C_T/C_P$ ). Note that the power is the electrical input power and does not account for any mechanical or electrical losses.

#### *Leading Edge Integration*

Figure 3.38 shows the performance comparison for the leading edge integration configuration. For the lower airspeeds, while the trends between the isolated and integrated EDF match, the isolated EDF has better performance at the lower advance ratios. For the higher

airspeeds, the trend flips with the integrated EDF having better performance. Based on the data, the increase in performance difference is dependent on the EDF advance ratio. This trend could be attributed to the coverage of the duct surface due to its integration by reducing the parasite drag at higher airspeeds.

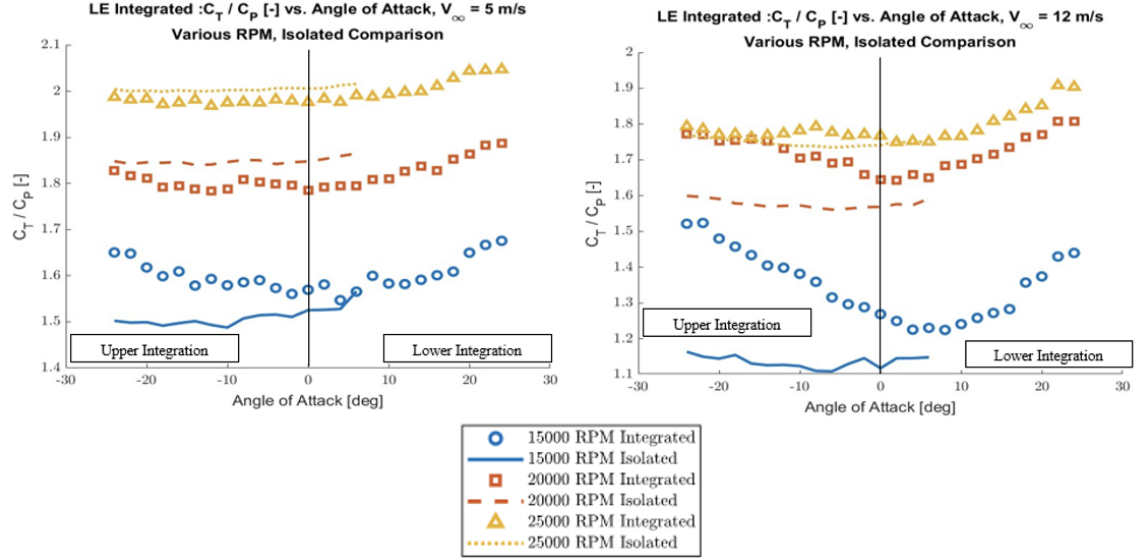


Figure 3.38: Non-dimensional power loading for leading edge integration at various conditions compared to isolated EDF for both surface integrations. Top figure at 5 m/s and bottom at 12 m/s

### Trailing Edge Integration

Figure 3.39 shows the performance of the EDF in the trailing edge configuration. Similar to the leading edge integration, the benefit in performance of the integration is mainly seen at higher advance ratios.

### 3.4.5 High-Frequency Loads and Acoustics

The high-frequency section of this results section analyzes the different integration configurations in the same figures as it is beneficial to understand common frequencies. With all configurations in the same figures, observed different resulting frequencies must be unique to the studied configuration.

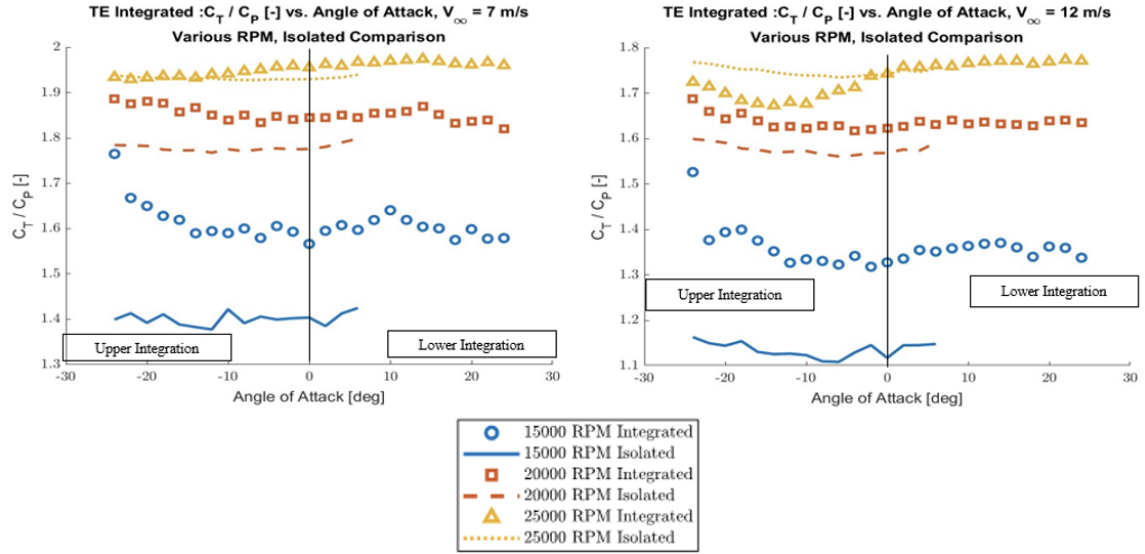


Figure 3.39: Non-dimensional power loading for trailing edge integration at various conditions compared to isolated EDF for both surface integrations. Top figure at 7 m/s and bottom at 12 m/s

Figure 3.40 shows the high frequency measurements for 12 m/s at 25k RPM case at various angles of attack. Figure 3.41 shows the acoustic high frequency measurements for the same testing conditions as the loads. Note that the two measurements were taken during the same experiment runs but are not time-synched.

### Leading Edge Integration

The middle column of Figure 3.40 shows the data at 0 angle of attack—the dominant frequencies observed from the leading edge integration case and the isolated EDF match. The dominant frequencies present in those cases are 14 kHz, 9 kHz, 4 kHz, and 2.5 kHz. The RPM frequency is also present, but it is not observable at this scale. Compared to the acoustic high-frequency data shown in Figure 3.41, the 14kHz frequency appears at a lesser magnitude, but its repeatability shows that the frequency must be associated with an aerodynamic effect. The acoustic data also indicates a dominant frequency of 5 kHz across all configurations, a frequency that is not dominant in the loads. This could be attributed to an internal bearing sound, which would have a noticeable acoustic effect but a minimal

impact on the loads.

### Trailing Edge Integration

The bottom row of both s Figure 3.40 and Figure 3.41 show the high-frequency data collected for the trailing edge integration. In Figure 3.40, this integration exhibits new dominant frequencies at 12.3 kHz, 11.8 kHz, and 10.7 kHz, which persist regardless of the angle of attack of the wing. These frequencies could be the frequencies at which the unsteadiness of the boundary layer is being ingested. For these testing conditions, the complete stall was never achieved, which could explain why the frequencies are constant for the various angles of attack. As noted before, the acoustic data shows a dominant frequency at 5 kHz for all the cases. Most dominant frequencies are below 5kHz for the trailing edge, with dominant frequencies showing at 2.4 kHz and 4.8 kHz. These also appear on the loads high-frequency analysis, pointing to an aerodynamic phenomenon.

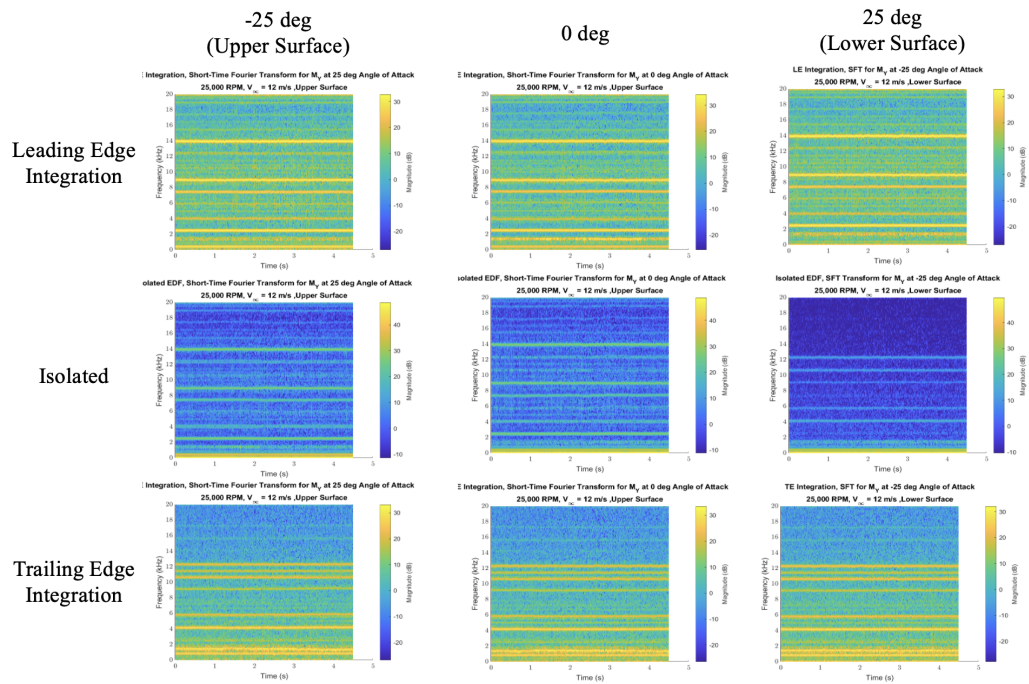


Figure 3.40: High frequency loads analysis ( $M_Y$ ) at various conditions compared to isolated EDF for both surface integrations at 12 m/s



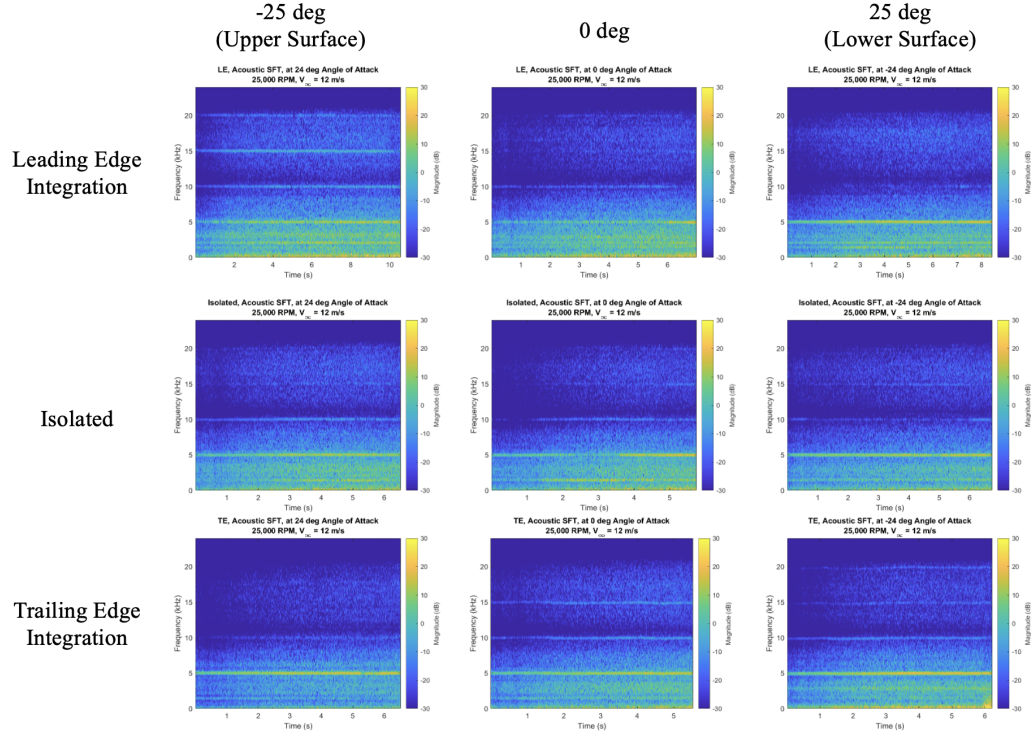


Figure 3.41: High frequency acoustics at various conditions compared to isolated EDF for both surface integrations at 12 m/s

### 3.5 Full Transition and High Speed Wing Integrated EDF Test

This section discusses the results of the second integration test where a Clark-Y duct EDF is integrated on the upper surface of an inverted Clark-Y 18% thickness airfoil. The results focus mainly on the EDF's thrust output, the duct's normal force generated on each integration, the power required, and a discussion on power loading. While the test rig was equipped with loadcells and pressure tubes on the wing section, those results are not discussed as they are outside of the scope of the thesis: where the goal is to understand the effects of the integration on the EDF itself. Unlike the previous section, the different integrations are sometimes presented on the same plots and compared with the isolated version, this is done to compare the aerodynamics. While the two integrations were not optimized for peak aerodynamic performance, the aerodynamic behaviour observed is representative of the integration. Some effects that are discussed can be mitigated when designing for it.

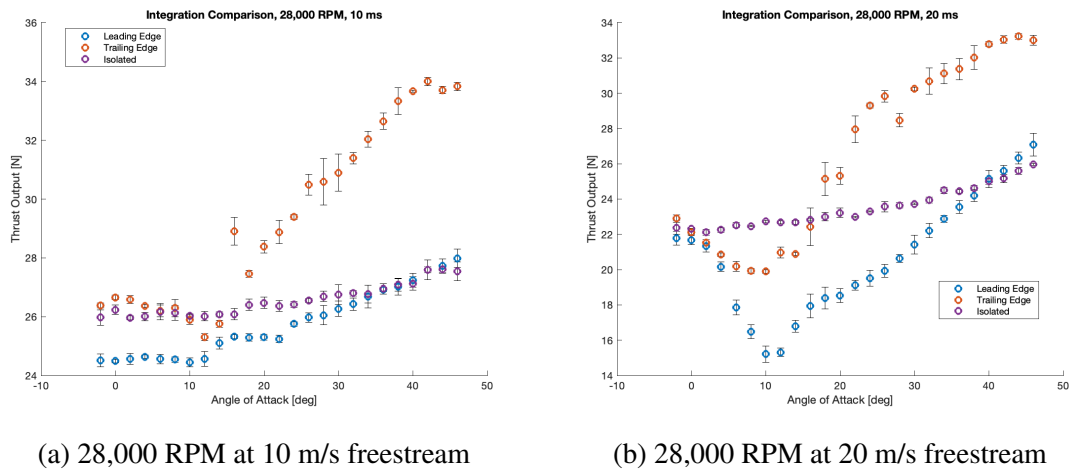


In this result section, 0 degrees represents the cruise condition, 90 degrees the edgewise, and 180 degrees represents vertical descent.

### 3.5.1 Thrust Output

As seen in the isolated EDF data, the thrust of the EDF is highly dependent on the inflow velocity and the interaction of the flow on the inlet lip. In this subsection, the thrust output is discussed, as well as how, by integrating on the airfoil, the inflow profile changes. Figure A.2 shows two edge cases from the test matrix. Figure A.2(a) shows a case where the inflow velocity generated by the EDF has a dominating effect, and the flow changes from the presence of the wing are minimal. Figure A.2(b) shows the 20 m/s freestream velocity case for the same RPM condition. The only thing changing between the two subfigures in Figure A.2 freestream velocity. As noted previously, as freestream velocity increases, the dominance of that flow over the one generated by the EDF suction increases. This shift in dominance highlights some external effects, like the influence of the wing.

When an airfoil is put in the flow, the air particles around the shape have a natural acceleration. The local velocity with respect to the freestream is more significant on the leading edge (sharp curvature) and decreases as it moves towards the trailing edge. This natural acceleration of the flow causes changes in the inflow velocity profile of the EDF.



(a) 28,000 RPM at 10 m/s freestream

(b) 28,000 RPM at 20 m/s freestream

Figure 3.42: Thrust output comparison for integration cases

The effects are seen on both subfigures of Figure A.2 but are more apparent in Figure A.2(b). At the cruise condition, it is observed that the leading edge integrated EDF produces 2.7% less thrust than the isolated case. In comparison, the trailing edge integrated produces 2.3% more thrust than the isolated. This is attributed to the nature of the EDF integration on the leading edge; as the inlet and the leading edge of the wing are flush, even in cruise condition, the wing causes an acceleration of the flow. A special case occurs at the trailing edge: boundary layer ingestion. In the cruise condition, the flow is probably not accelerated enough to cause a decrease in thrust. Still, part of the EDF fan is ingesting the boundary layer (BL) of the wing, which creates a region of lower velocity. In cruise, the positive effects of the BL outweigh the thrust reduction caused by the flow acceleration around the airfoil. This trend is observed across all test conditions. These conditions change as the airfoil continues pitching up until stall (12 degrees). A significant drop in thrust output is observed between the cruise and stall angles for the leading edge integrated EDF. The difference in the test case shown in Figure A.2 is a drop of 34.4%. The trailing edge EDF shows a similar but less aggressive trend, showing a decline of 14%. This gives a glimpse of the stall behavior of the system. By integrating the EDF on both edge cases, the stall behavior is much more complex; there is a sudden loss of lift and a significant loss of thrust. The post-system stall behavior is interesting as well. For the leading edge integrated EDF, the thrust recovery is slow, reaching the same thrust output as the isolated version until 40 degrees of angle of attack. On the other hand, the trailing edge integrated EDF matches the thrust of the isolated version at 16 degrees of angle of attack. Between stall (12 degrees) and 20 degrees, the leading edge EDF increases its thrust output by 19% while the trailing edge integrated EDF increases its output by 18.7%. Similar effects are shown in Figure A.2(a) but to a lesser magnitude. Note that the trailing edge integrated EDF shows increases of thrust up to 4 degrees of angle of attack due to BLI.

The trailing edge integrated EDF produces more thrust than its isolated version for angles above 16 degrees. Once the wing stalls, a pocket of reverse or slow-moving flow

is created, especially close to the trailing edge. Shedding from the wing's lower surface towards the EDF could also enhance the thrust output. For the case shown in Figure A.2, the thrust produced by the trailing edge integrated EDF is 23.9% higher than the isolated version.

#### *Closer look to the leading edge integration*

As discussed previously, integrating the EDF onto the leading edge creates a drop in thrust that is maximized until stall and then shows a slow recovery. This is due to the acceleration of the flow that the presence of the wing creates, and as expected, the effect is enhanced with airspeed. Figure 3.43 shows the trend for two studied RPMs at various airspeeds. The trend is magnified at higher advance ratios where the freestream flow dominates over the thrust induced flow. in Figure 3.43(a) at 20 m/s, the drop in thrust between cruise and stall (12 degrees) is 55% while Figure 3.43(b) the drop in thrust is 29.6%.

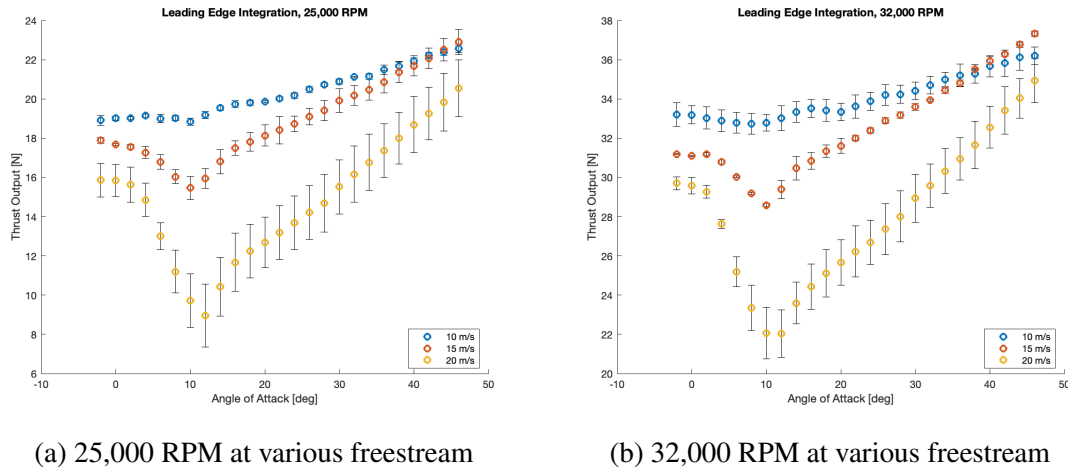


Figure 3.43: Thrust output comparison for leading edge integration, constant RPM, and various airspeeds

#### *Closer look to the trailing edge integration*

As discussed above, the trailing edge behavior is similar to the leading edge, with a decrease in thrust leading up to stall. The key difference is that the loss of thrust is less aggressive,

and the recovery is more aggressive, even surpassing the thrust output of the isolated EDF by 23.9% in some cases. Figure 3.44 shows the results of 2 RPM cases. The interesting behavior is that after a certain point (in this case, 16 degrees), the thrust output of the EDF becomes independent of airspeed.

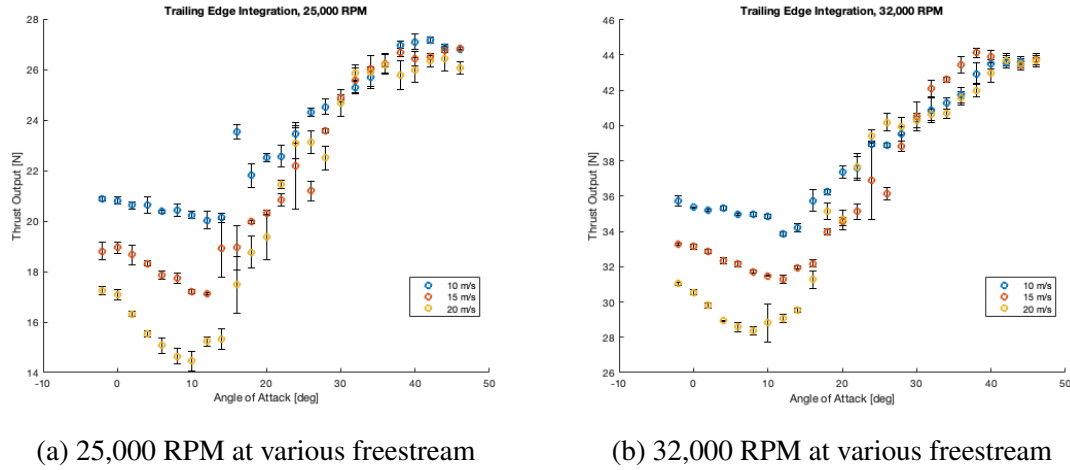


Figure 3.44: Thrust output comparison for trailing edge integration, constant RPM, and various airspeeds

Once again, the flow speed dominance defines the magnitude of the thrust loss leading up to the stall. In Figure 3.44(a), where the freestream is more dominant than the thrust induced flow, a thrust reduction between cruise and stall (12 degrees) of 17.6% is observed. While in Figure 3.44(b), only a 7.38% decrease is observed for the 20m/s case.

### *Unusual Attitudes - Edgewise Flight*

This subsection explores the thrust output of the integrated EDFs for edgewise flight (70 degrees to 110 degrees). As shown on the test matrix, these tests were conducted at the Low Turbulence Wind Tunnel's exhaust to achieve a better freestream velocity resolution at lower airspeeds. This section only presents some cases, as all the observed trends are similar.

Figure 3.45 shows the thrust output for both integrations, and they show similar trends. In both cases, the thrust output is constant with a slight (less than 1%) decrease as it pitches

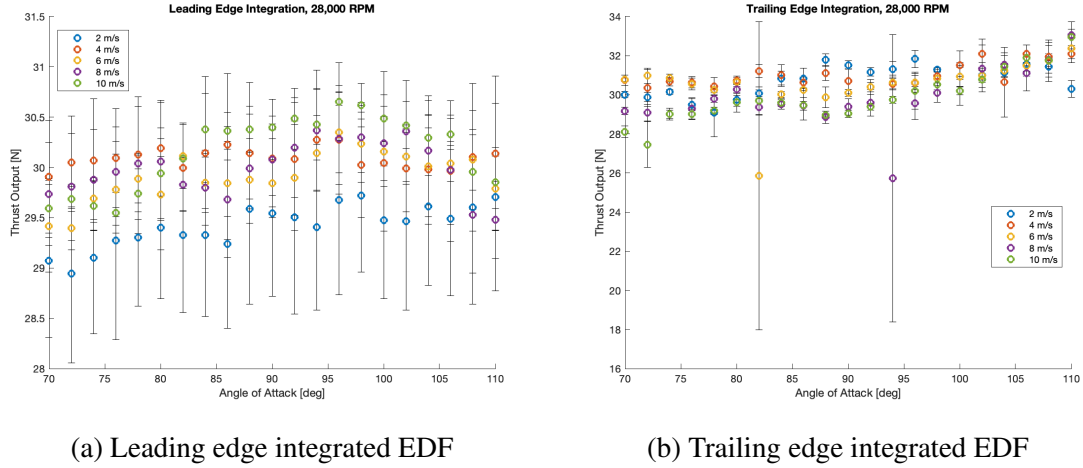


Figure 3.45: Thrust output comparison for unusual attitudes - edgewise flight at 28,000 RPM

into the flow and an enhancement as it pitches away from the flow. This enhancement can be attributed to the increased back pressure on the exhaust and some viscous forces acting in favor of the EDFs thrust production. This trend is similar to the ones observed on the isolated tests discussed earlier in this chapter.

### *Unusual Attitudes - Descent Flight*

This subsection analyzes the thrust output of both integrations when the system is in an airbreak or complete descent case (120 degrees to 180degrees). Airbreak happens when the EDF is not completely in descent, but the exhaust is pointed towards the freestream to slow down a vehicle in flight.

Figure 3.46 shows the results for the EDFs on that condition. Figure 3.46(a) shows the leading edge integrated EDF. The behavior of the leading edge integrated EDF is similar to the isolated with fairly constant thrust output across all angles due to higher back pressure and viscous forces; when the freestream is higher there is an increase in thrust as the full descent case is approached. In the case shown in Figure 3.46(a), the increase in thrust observed between 120 degrees and 180 degrees for the 10 m/s case is 3.56% while for the 2 m/s case, the thrust decreased by 1.3% (note that this difference is within the margin of

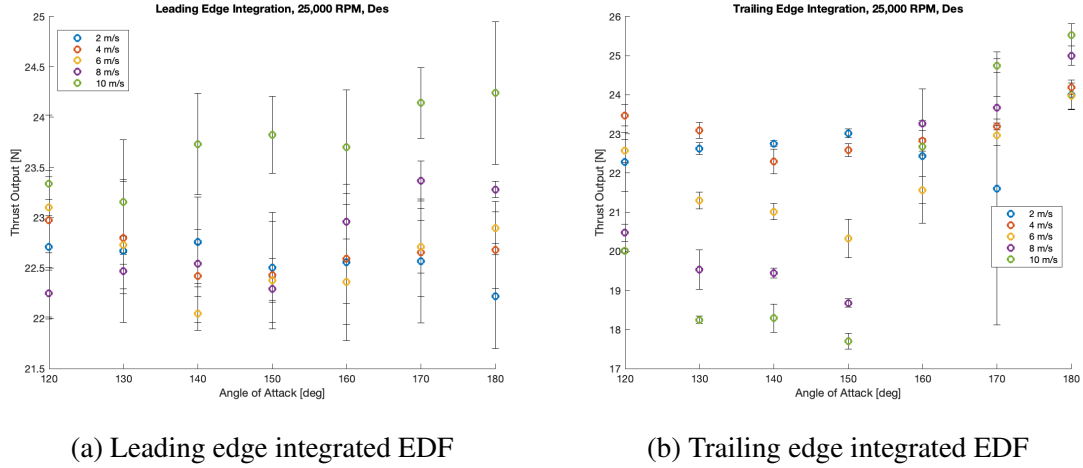


Figure 3.46: Thrust output comparison for unusual attitudes - airbreake and descent flight at 25,000 RPM

error of the equipment). Figure 3.46(b) shows the results for the trailing edge integration. A trend observed is that the thrust output jumps between 150 degrees and 160 deg. This is attributed to the fact that in between those angles, the EDF's exhaust is no longer on the wake of the wing system, completely exposing it to the freestream. For the 10 m/s case, there is a 22.7% increase in thrust, while the 2 m/s case sees a 1.6% decrease (within the margin of error of the measuring equipment). Note that the measurements become increasingly unsteady between 150 degrees and 160 deg.

### 3.5.2 Normal Force

The normal force discussed in this section is of the duct. It is not called lifting force as the force was not transformed with the angle of attack due to drag measurement contamination from the thrust. Figure 3.47 shows some results that represent the important aerodynamic trends. Before diving into the results, let us take a step back and recall the aerodynamics of the isolated duct. The duct on the EDF is an annular symmetrical wing. This means that it should not produce any lifting force in the cruise condition as all its internal forces are balanced. This case shows Figure 3.47, where the isolated EDF produces 0 normal force at the cruise condition.

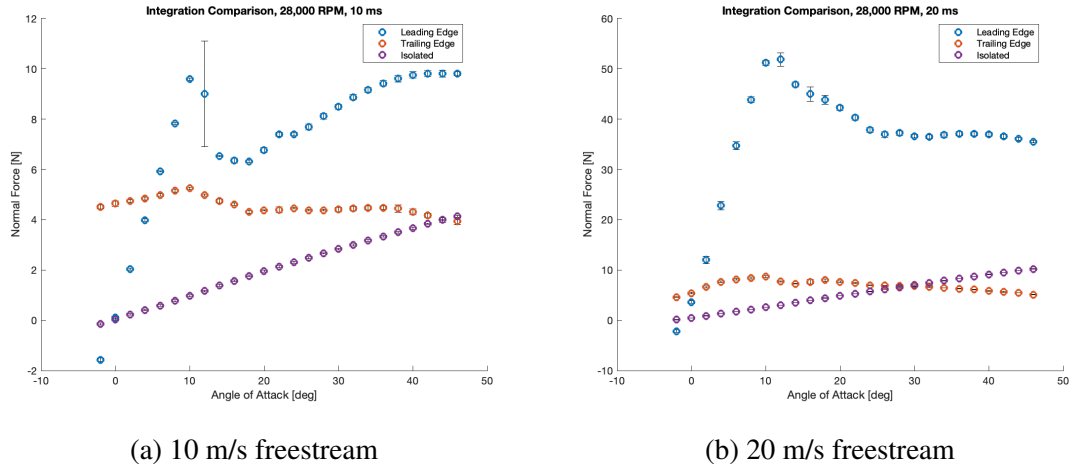


Figure 3.47: Normal force comparison at 28,000 RPM at various freestream velocities

Similar trends are shown on both sub-figures, so the discussion Figure 3.47(b) is referred to discuss the phenomena. When integrating the duct in any way, the symmetry of the isolated duct is invalidated. In both cases, the lower surface of the duct is immersed in the wing (where there is no freestream velocity), hence creating a very large high-pressure region on the lower surface of the duct. Focusing on the leading edge integration, it is observed that its normal force production is more significant (135.8% at the maximum peak) than the normal force produced by the trailing edge integration. This effect goes back to the stronger influence that the airfoil has on the flow around the leading edge. More curvature means a larger velocity gradient in the region. The acceleration of the flow on that region, coupled with the induced rotor flow and the possibly artificially created high-pressure region under the duct; the leading edge integration is able to produce very high normal forces. The peak occurs around 12 degrees when the exterior of the duct stalls. A very similar but reduced magnitude effect is observed on the trailing edge integrated EDF. Still, the normal force at its peak for the trailing edge integrated EDF is 85.7% larger than the isolated case. Figure 3.48 shows a closer look at the effects on the leading edge and the trailing edge integrations. The dimensions are non-dimensionalized as the duct is under the influence of the EDF so neither a rotorcraft literature non-dimensionalization nor a classic aircraft normalization was suitable.

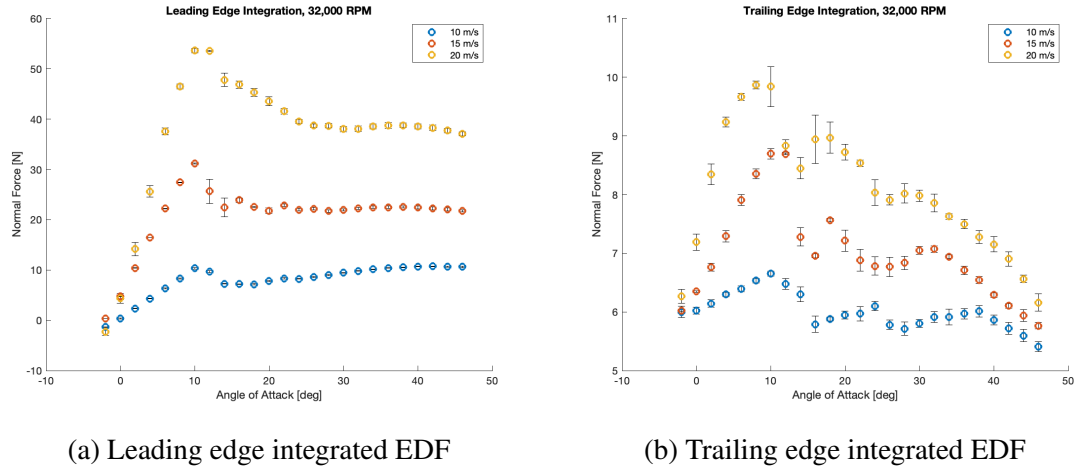


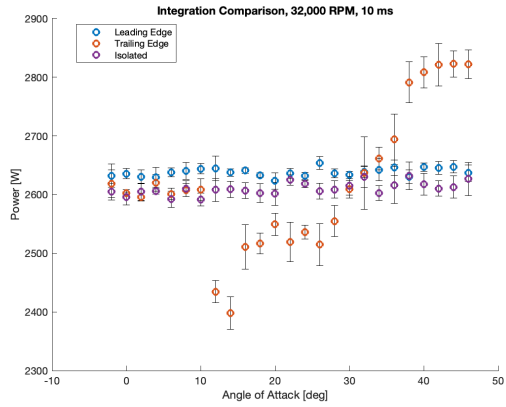
Figure 3.48: Normal force at 32,000 RPM at various freestream velocities

### 3.5.3 Electrical Power Required

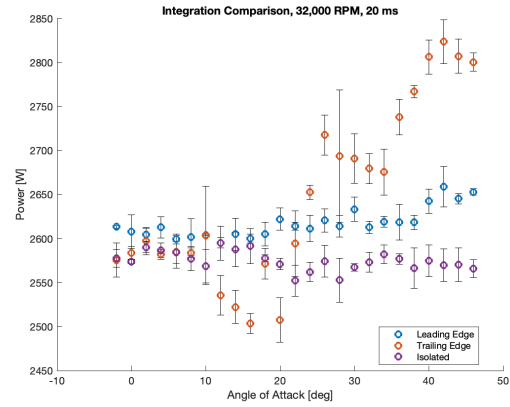
The electrical power provides an insight into the mechanical power required by the system to maintain constant RPM given a condition. Due to construction constraints, it was impossible to measure the shaft power directly; the stator vanes also made it impossible to measure based on the restoring moment on the loadcell measuring plane. Assuming a system efficiency of 71% as quoted on the motor spec sheet, the mechanical power can be assumed to be 71% of the measured electrical power values. Figure 3.49 shows the results of some representative cases. The leading edge integrated EDF showed similar behavior to the isolated EDF. Mostly linear without increasing with angle of attack. Overall, the isolated EDF required between 1.38% and 3.33% less power than the leading edge integrated EDF.

An interesting trend is noted on the trailing edge integrated EDF case. As the stall region approaches, the overall power required to maintain a constant RPM drops 2.9%, and then post-stall it increases by 8.2%.





(a) 10 m/s freestream

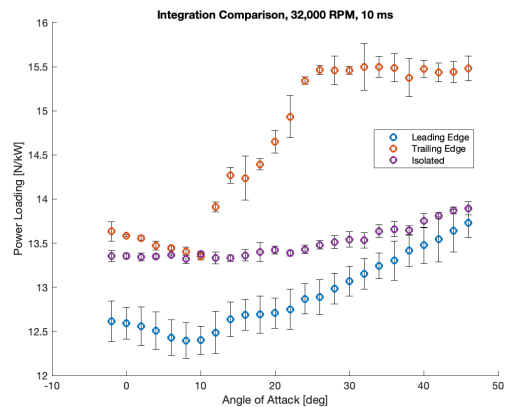


(b) 20 m/s freestream

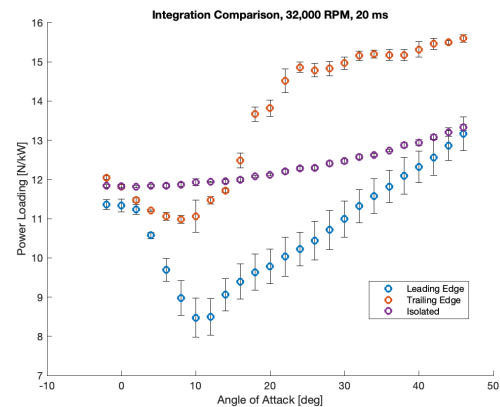
Figure 3.49: DC power comparison at 32,000 RPM at various freestream velocities

### 3.5.4 Efficiency Discussion - Power Loading

The power loading was selected as the efficiency metric. Note that the power is the electrical input power and does not account for any mechanical or electrical losses. The lack of instrumentation on the exhaust does not permit the calculation of the propulsive efficiency as done in the isolated tests. Figure 3.50 shows two representative cases. As expected, the trends follow similar trends to the thrust plots shown in the thrust output discussion. As a constant RPM test, the power required was expected to remain fairly constant, making the thrust the dominating term on the equation.



(a) 10 m/s freestream



(b) 20 m/s freestream

Figure 3.50: Power Loading comparison at 32,000 RPM at various freestream velocities

Overall, the leading edge integrated EDF is less efficient than the isolated EDF. Figure 3.50(a) shows that in cruise condition, the leading edge integrated EDF was 7.7% less efficient than the isolated EDF. The difference shown in Figure 3.50(b) decreased to 4.29%; showing a correlation that at lower advance ratios, the EDFs start to perform similarly eventually to converge on the static case. In contrast, the trailing edge integrated EDF was more efficient in the cruise condition, between 1.3% and 2% more efficient than the isolated case. This difference was independent of the advance ratio. At the highest angle of attack tested, the trailing edge EDF was 16.7% more efficient than the isolated and the leading edge integrated EDF for the 20 m/s case shown in Figure 3.50(b). As the angle of attack increased, the performance of the leading edge integrated EDF and the isolated version converged.

### **3.6 Simplified Aerodynamic Forces on Integrated EDF**

The discussion above provided general trends that give insights into what might be occurring locally. As mentioned, placing an airfoil in the flow will naturally accelerate the air around the surface. The aero-propulsive coupling due to the presence of the airfoil on the EDF can be simplified in a diagram similar to Figure 1.1. Figure 3.51(a) shows the duct and rotor forces and moments in the cruise condition. The results from the symmetrical wing showed that the leading edge integrated EDF was moment balanced in the cruise condition. The results from the inverted Clark-Y wing test showed reduced thrust, possibly due to the flow acceleration on the wing's leading edge. Figure 3.51(b) shows the forces in a pre-wing-stall phase; in simplified terms, the aerodynamic forces act similarly to the isolated EDF. The results from the symmetrical wing showed that the destabilizing moment was reduced in magnitude, possibly due to a higher flow acceleration on the windward side of the rotor and a reduction of effectiveness on the windward inlet lip. Figure 3.51(c) shows that the deep stall simplified aerodynamic forces remain similar to the pre-wing-stall condition and the isolated EDF forces.

Figure 3.52 shows the simplified aerodynamic forces on the trailing edge integrated

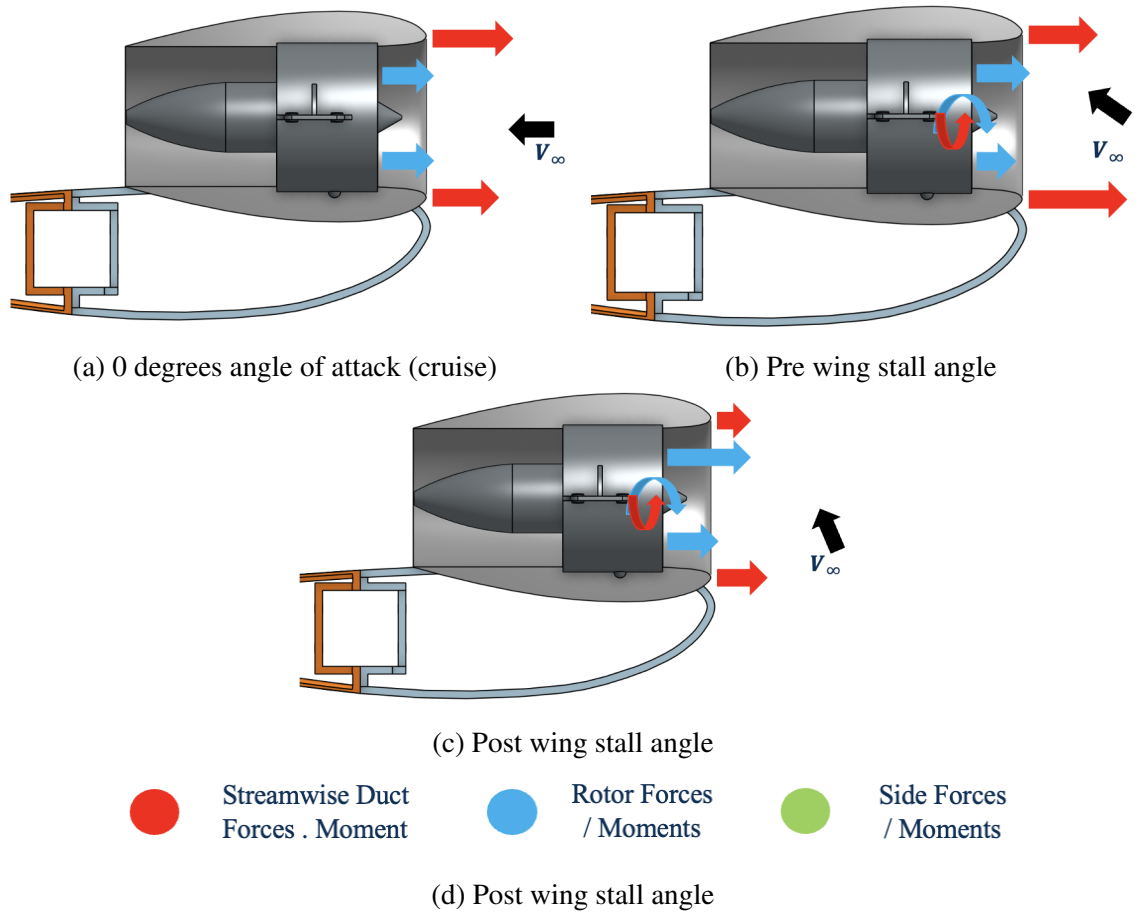


Figure 3.51: Leading edge integrated EDF simplified aerodynamic forces diagram

EDF. Figure 3.52(a) shows the duct and rotor forces and moments in the cruise condition. Unlike the isolated case, the trailing edge integrated EDF does not have a balanced moment in cruise. The integration on the trailing edge immerses the windward lip of the inlet into the wing, preventing it from producing a streamwise force. The duct forces are imbalanced in all angles of attack, as shown in the results from the symmetrical wing. When pitched up, the construction always provides a stabilizing moment. The rotor forces show an opposite effect to the isolated; the windward side of the rotor produces more thrust due to the reduced velocity region created by the airfoil's boundary layer. The leeward side of the duct produces less thrust due to the suspected increase in local velocity due to the presence of the wing. The pre-wing-stall condition is shown in Figure 3.52 (b), and the simplified aerodynamic force diagram remains unchanged. The magnitude of the thrust produced on

the leeward side of the rotor decreases due to a possible flow acceleration as the airfoil nears stall. In this case, the rotor forces are destabilizing. Figure 3.52 (c) shows the force diagram with the wing in a post-wing-stall case. As noted on the Clark-Y tests, the thrust of the EDF becomes independent of airspeed, meaning that the wing's wake creates a low-velocity zone that causes the EDF to produce more thrust. The rotor forces are balanced, and the duct still produces a stabilizing moment.

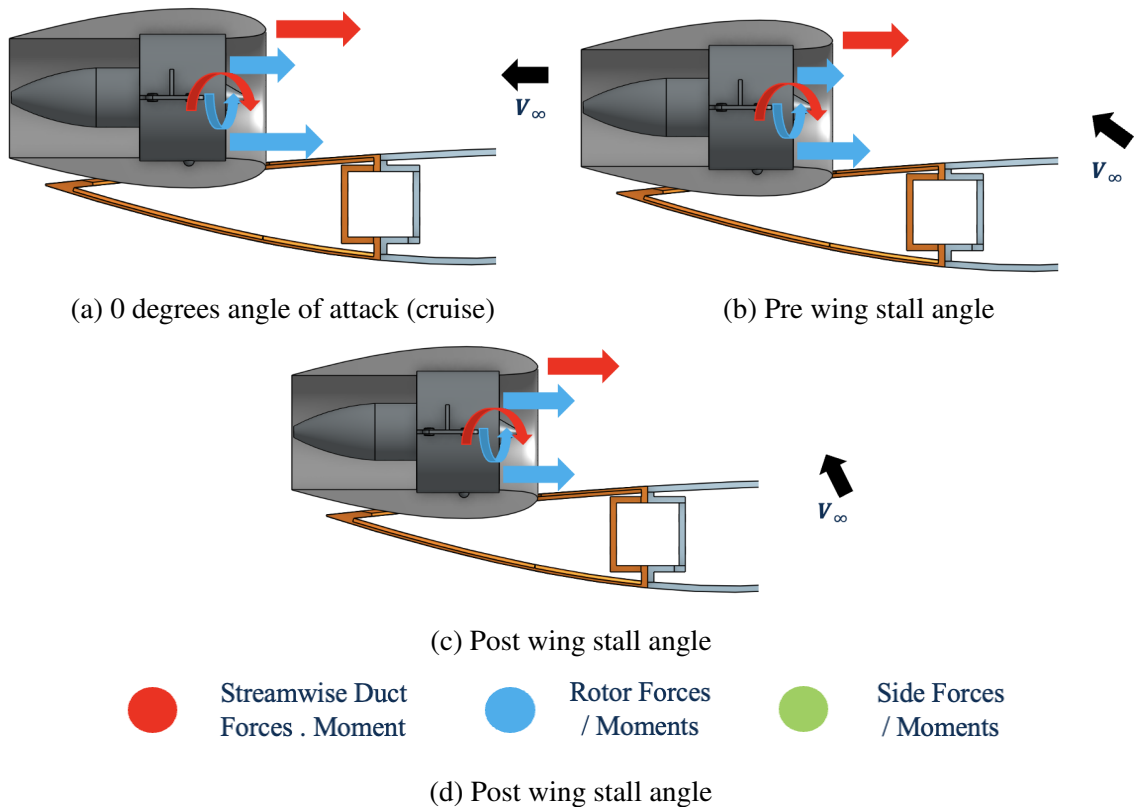


Figure 3.52: Trailing edge integrated EDF simplified aerodynamic forces diagram

## **CHAPTER 4**

### **CONCLUSIONS**

Wing blended electric ducted fans (EDF) and isolated EDF are on the rise as a solution to increase efficiency on regional mobility platforms. Electrification of platforms has permitted the introduction of novel integration concepts that use phenomena like BLI to enhance their performance. The lack of complex mechanical links helps designers to place propulsive devices practically anywhere on the aircraft, opening a field of opportunities for research and development. As noted in the literature review section, little attention has been given to understanding the effects of novel integrations on the EDF. This research explored and compared how a wing leading edge or a trailing edge integrated EDF changes its behavior and performance at velocity conditions. To address this gap in the literature and enhance our understanding of various integration techniques, this effort addressed the following objectives:

- Does a leading edge integrated EDF show similar characteristics to the isolated EDF?
- How does the chord-wise location of the EDF wing integration affect the performance of the EDF?
- Does integrating the EDF on the upper surface or lower surface change the behavior of the EDF for the same chord-wise integration position?

The first question the research wanted to answer regards the performance of the leading edge integrated EDF compared to the isolated. Both integration tests showed that the behavior for a leading edge integrated EDF that has the inlet flushed with the leading edge is similar in performance to the isolated case for low airspeeds. The behavior starts to diverge as the airspeed increases. This shows that the isolated and the leading edge integrated

perform similarly at low advance ratios (where the induced flow from the fan dominates). Once the airspeed increases and the EDF enters a higher advance ratio regimen, the wing's effects on the surrounding velocity field increase, causing a behavior divergence. It was observed that the leading edge integrated EDF showed a drop in thrust between 30% and 55% when the wing system is approaching stall. This was attributed to the large velocity gradient near the leading edge caused by the airfoil. As the angle of attack increases, the integrated version and the isolated behavior start to converge. From a performance perspective, it was shown that the leading edge integrated EDF was around 3% less efficient than the isolated version. From a pitching moment perspective, both the isolated and the leading edge integrated EDF showed similar trends, with the integrated version having a destabilizing moment of lesser magnitude. That is because when the wing accelerates the flow, the rotor side closer to the wing will produce less thrust, increasing the stabilizing moment and inducing thrust imbalance.

The second question that was answered by the work done regards the effect of the EDF's chord-wise location on its performance. This study studied both edge cases: the leading edge integration and the trailing edge. The results from the Harper tunnel help explain that phenomenon the best as the aerodynamic trends are enhanced at higher speeds. As discussed, the airfoil creates a velocity gradient (with respect to the freestream) along its surface; the gradient is larger towards the leading edge and decreases as it approaches the trailing edge. The leading edge integrated EDF showed more substantial effects from the integration than the trailing edge. On the leading edge, sharper loss of thrust is observed up until stall and then a slower recovery, matching the thrust output of the isolated until 40 degrees of angle of attack. On the other hand, the trailing edge integrated EDF saw a less aggressive loss of thrust of 14% (for the presented cases) and a quicker thrust recovery post-stall, matching the isolated at 16 degrees of angle of attack. The trailing edge also saw benefits from BLI, with thrust increasing up until 6 degrees of angle of attack due to the thickening of the boundary layer (which brings less accelerated flow). As the power

required remained relatively constant, these conclusions also match the ones from the performance, defined as power loading. Moving the EDF further towards the trailing edge is beneficial for performance due to a smaller velocity gradient by the airfoil presence and the introduction of BLI.

The last question sought to be answered was the effects of doing a lower surface or an upper surface integration on the performance of the EDF. This was responded to through the tests on the symmetrical airfoil rig on Low Turbulence Wind Tunnel. From a thrust perspective, doing either integration has similar effects with an overall thrust output of less than the isolated case for the higher advance ratios (due to the discussed influence of the wing). For the studied cases, the trailing edge integrated EDFs on the wing's upper surface produced less thrust than its counterparts on the lower surface. The pitching moment is more interesting. For the leading edge case, the upper surface integration follows the trend of the isolated EDF while the lower surface becomes angle of attack independent, especially at higher advance ratios. For the trailing edge integration, there is a constant pitching moment independent of the angle of attack. In contrast to the leading edge integration, the trailing edge integrated duct always has a surface immersed into the wing. The upper side of the inlet lip produces a thrust that pitches the EDF always into the wing.

These are the general conclusions that help address the fundamental questions that were sought to be answered in the proposal. Chapter 3, Results and Discussion, analyzes and explains various aerodynamic trends observed in all three testing campaigns that form this thesis work.

## **CHAPTER 5**

### **FUTURE WORK**

The work started in this thesis explored only the performance effects than an integration has on the performance and force/moment output of an integrated EDF. The first step to continue this work is to characterize the velocity flow field around the EDF and the aeropropulsive lifting system. This investigation will provide insights onto the root causes of the increase of inflow velocities (or decreases). This can be achieved through the implementation of PIV to resolve the flow field around the EDF. As shown on this work, doing PIV up to the fan stage of the EDF presents its challenges due to reflection from the blades and the velocity of the RPM. In order to resolve the inflow velocity to the rotor (which will give more information about the thrust output) other techniques should be coupled with PIV to get a more complete picture. One technique is to use a pitot rake in the inlet of the duct or traverse a single tube (ensure its small in diameter to minimize flow contamination) to obtain an inflow profile. The addition of pressure ports on the inlet of the EDF for the integrated cases might also provide insight on flow separation and inlet distortion. If this work would have a following entry it would be suggested to reduce the test matrix to explore only the stall region of the wing, this means do a fine sweep of parameters between 5 degrees and 20 degrees. The addition of these tests will complete the aerodynamic picture of the integrated EDF between the cruise condition and edgewise flight. Transient tests could be designed to understand how the dynamic loads of a high speed rotating body (lots of inertia) transfer to the system. Another area that would be interesting to explore is ground effect of such devices: how will the thrust output change once the vehicle approaches the ground, a state where the thrust level is at is highest.

With the complete aerodynamic picture and insights on the inflow in the EDF fan stage other fields enter play. From a structures perspective, how does the transition generate



oscillatory loads that affect the blade design and hub design. Currently, the EDFs on the market and conventional turbofans have a rigid hub that is not designed for such loads. With the expectation that regional mobility vehicles operate at high rates, looking into these topics might be worth while for enhanced safety and certification procedures. The field of aircraft/rotorcraft controls could be opened to understand how this aero-propulsive coupling drives controller design. As seen on this research, the thrust of the integrated EDF is highly coupled with the stall behaviour of the wing; with these vehicles there would be situations where stall means a loss of thrust and lift.

# **Appendices**

## **APPENDIX A**

### **DEVELOPMENT OF TECHNIQUE TO MEASURE 1-D VELOCITY FIELDS**

Having a clear understanding of the flow field at the rotor plane is of utmost importance to characterize phenomena like inlet distortion or rotor oscillatory loads. Classic methods to resolve the flow field like PIV become extremely complicated for ducted fans because of the lack of optical accessibility and rotor blade reflections. A new method is being developed to measure the inflow velocity close to the rotor plane using thin hot wire (similar to that used by foam cutters). The hypothesis for the method is that by measuring the fluctuation of temperature of the wire, the 1-D velocity on that location can be resolved. The method consists on placing a fine Nichrome wire in the area of interest and measure the changes in temperature using a radiometric thermal camera. The wire proposed for this method is a 0.12 mm (37AWG) superfine heating wire. A small thermal camera will be used to measure the changes in temperature. The selected hardware for this is the Lepton 3.5 by TELEDYNE FLIR. The device has the footprint of a dime (17.39 mm) coin and has a field of view 57 degrees with a 19,200 pixel (160x120) resolution [13].

#### **A.1 Proof of Concept Rig Design**

The first step on the development of the technique was to test the capability to capture a trend between measured wire temperature and freestream velocity. For this a rig was designed for the Aerolab educational wind tunnel at Georgia Tech. The tunnel is capable of velocities up to 140 mph making it suitable for the calibration task. Figure A.1 shows the design of this rig. The hot wire is traversed across the middle of the test section of the Aerolab tunnel and connected to power from the outside. The FLIR camera is placed upstream in the flow with a view at 45 degrees of the wire. The tunnel was then swept at various airspeeds. Note that the side panels of the Aerolab tunnel are plexiglass. Initial

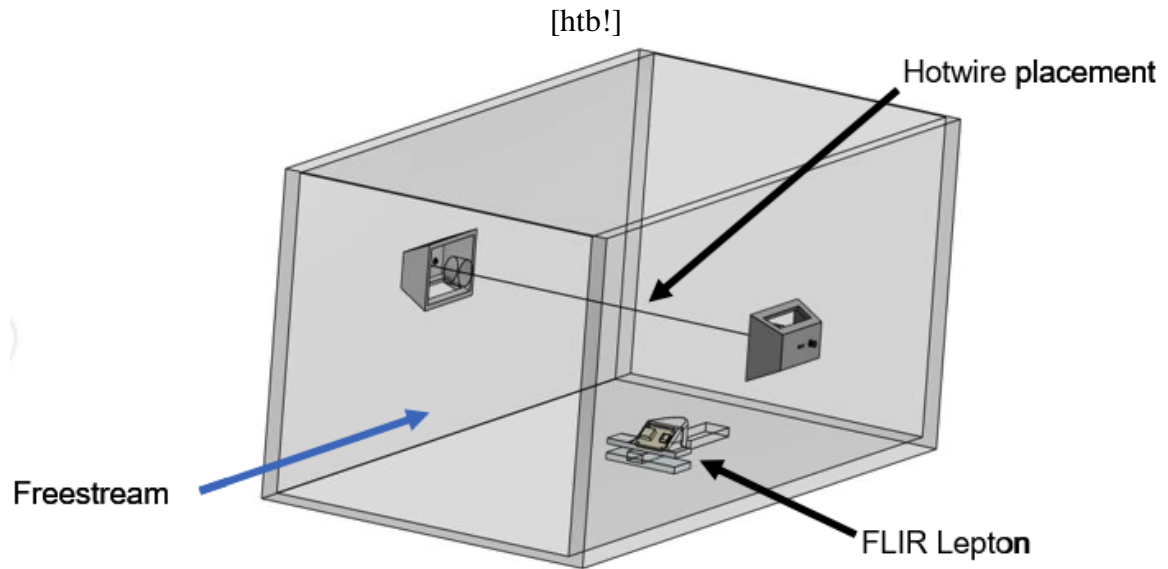


Figure A.1: Educational wind tunnel test rig for hot wire calibration

testing found that the plexiglass act as as a mirror for IR waves. To avoid this, PIV black paper was added to the sides and top of the tunnel.

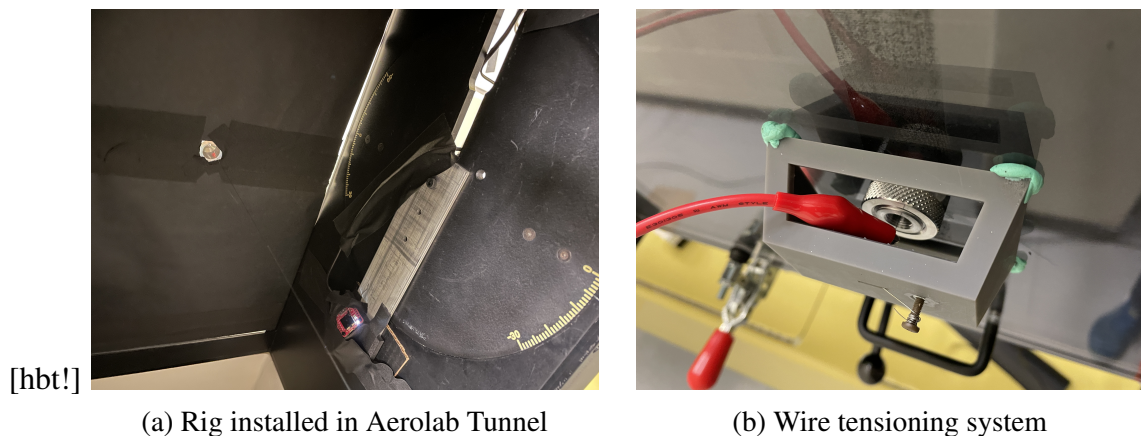


Figure A.2: Rig construction in Aerolab Tunnel

Another topic that wanted to be studied was the ability of the method to capture large temperature gradients. To test this, a cylinder was placed 2 diameters upstream of the hot wire and attached to the tunnel via tape and ran at 10 m/s.

## A.2 Preliminary Results

The preliminary results shown on Figure A.3 show a trend between the temperature recorded and the velocity of the tunnel. The resolution at which velocity can be resolved is only a window of 5 m/s. In order to obtain a larger window a controller with a temperature schedule should be implemented. The issues with a constant power supply it that in order to get a larger window, the wire must heat up beyond its capability without external cooling. The results from Figure A.3 show an exponential trend, as expected from the relationship between Reynolds number (velocity) and Nusselt number for a wire, the relationship is shown on Equation A.1.

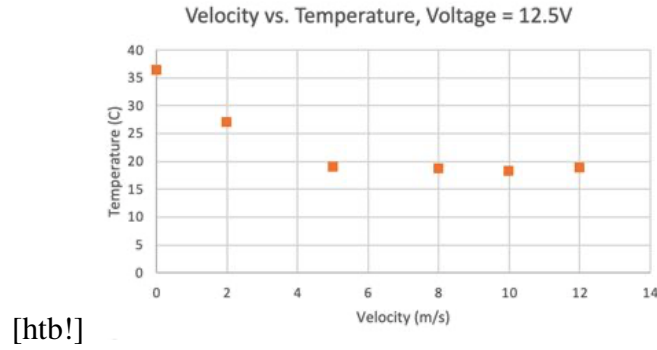


Figure A.3: Velocity vs Temperature profile at 12.5V

$$Nu = 0.989 Re^{0.330} Pr^{1/3} \quad (A.1)$$

To experiment with the capability of the system to capture large temperature gradients, the wake of the cylinder was visualized using the hot wire method. The figure shown on Figure A.4 is the time average of 100 frames of radiometric data from the FLIR Lepton. Note that the wake region of the cylinder is well defined. When observing the video compilation of the frames, unsteadiness in the temperature near the wake region is apparent. This changes in temperature can be related to the vortex shedding from the cylinder. The hot region away from the wake of the cylinder is blockage from the tape clamping down the object.

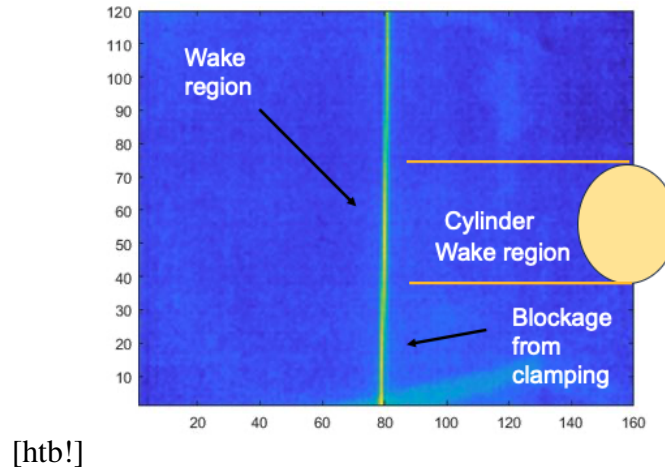


Figure A.4: Measurement of cylinder wake

### A.3 Conclusion and Future Work

The novel method to visualize 1-D flowfields showed promising preliminary results by creating a repeatable trend and by showing that the wake region behind a cylinder can be characterized. A theoretical relationship between the velocity and temperature obtained via the Nusselt number did not match the experimental results. This is attributed to the fact that the Nusselt number equation requires the temperature on the body. Due to the low emissivity of the wire, the FLIR is measuring the reflection of the heat and not the surface temperature, causing erroneous measurements. A closer calibration on distance from the wire vs temperature will be required to match theory. The method could be useful for flight testing where PIV is inaccessible, hot wires could be placed strategically with the small cameras and that way generate flow fields in mid flight.

## APPENDIX B

### COMPREHENSIVE SET OF ISOLATED EDF DATA

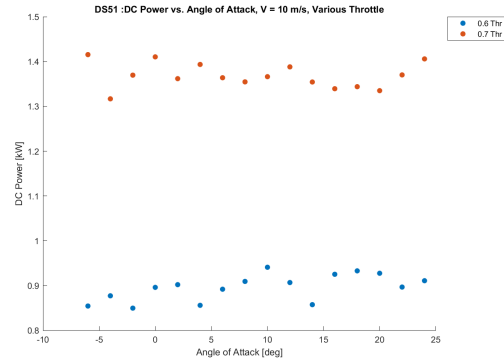


Figure B.1: DC Power vs. Angle of Attack, V = 10 ms, Various Throttle

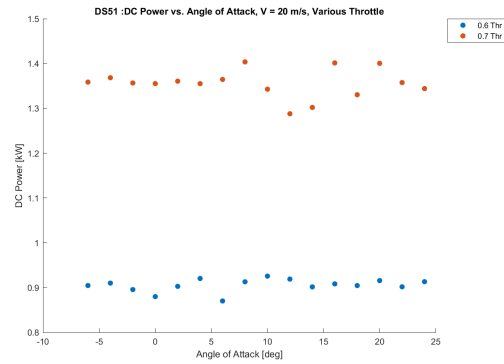


Figure B.2: DC Power vs. Angle of Attack, V = 20 ms, Various Throttle

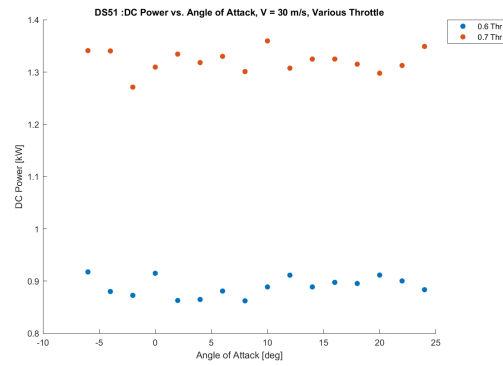


Figure B.3: DC Power vs. Angle of Attack,  $V = 30$  ms, Various Throttle

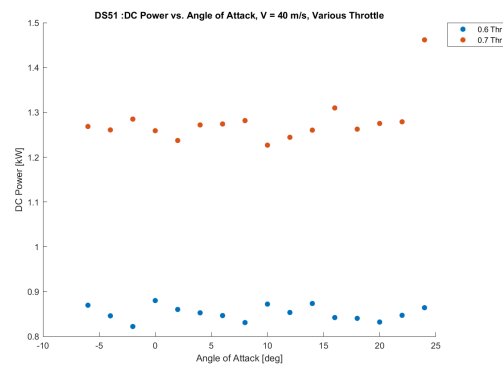


Figure B.4: DC Power vs. Angle of Attack,  $V = 40$  ms, Various Throttle

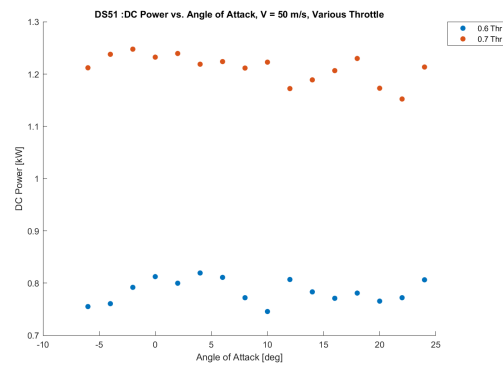


Figure B.5: DC Power vs. Angle of Attack,  $V = 50$  ms, Various Throttle



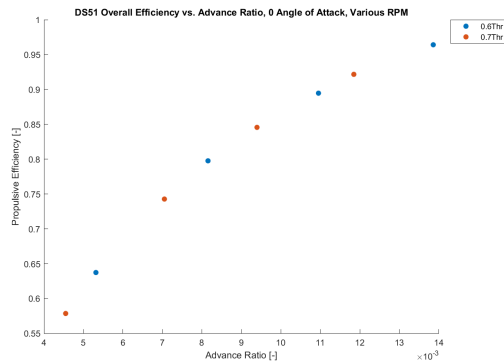


Figure B.6: DS51 Overall Efficiency vs. Advance Ratio, 0 Angle of Attack, Various RPM

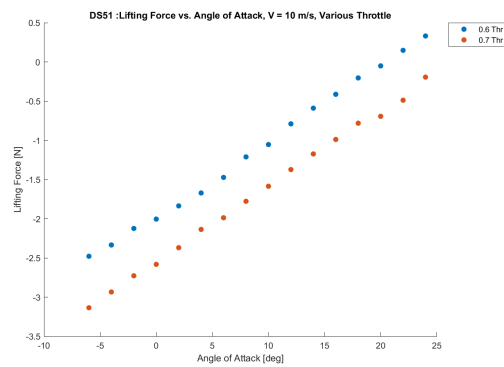


Figure B.7: Lifting Force vs. Angle of Attack, V = 10 ms, Various Throttle

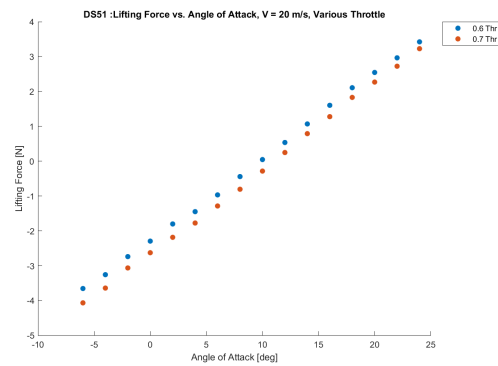


Figure B.8: Lifting Force vs. Angle of Attack, V = 20 ms, Various Throttle

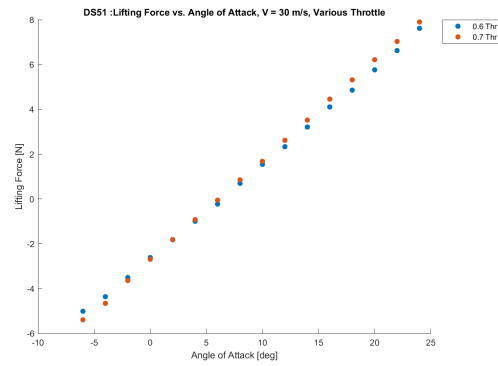


Figure B.9: Lifting Force vs. Angle of Attack, V = 30 ms, Various Throttle

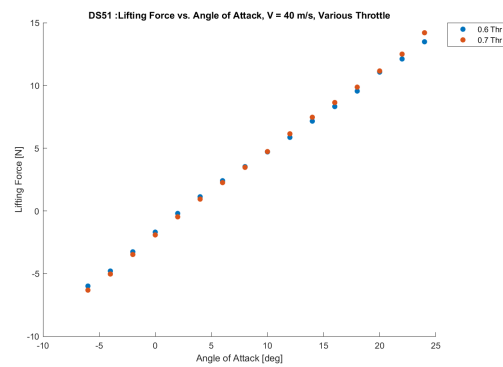


Figure B.10: Lifting Force vs. Angle of Attack, V = 40 ms, Various Throttle

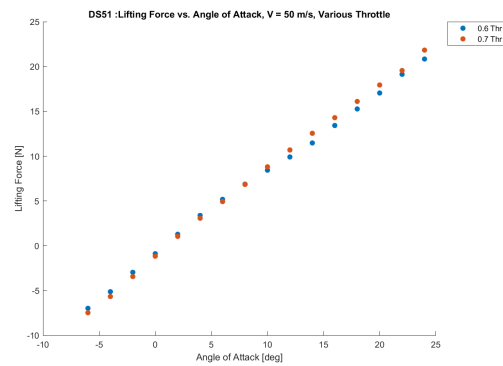


Figure B.11: Lifting Force vs. Angle of Attack, V = 50 ms, Various Throttle

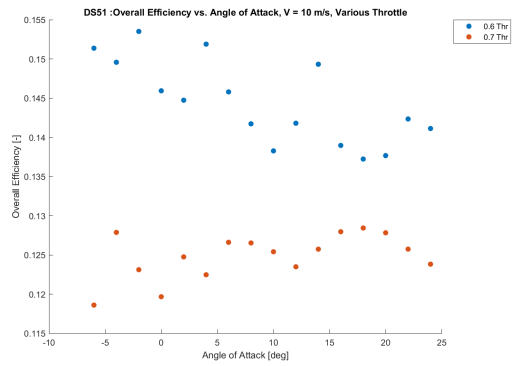


Figure B.12: Overall Efficiency vs. Angle of Attack,  $V = 10$  ms, Various Throttle

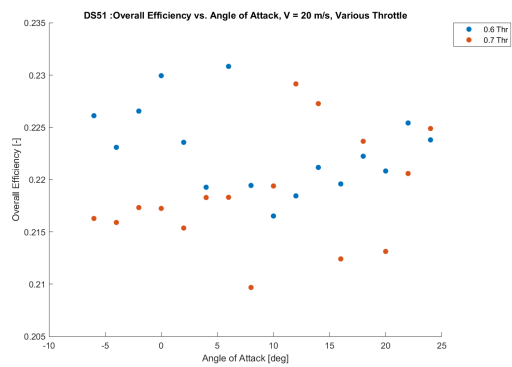


Figure B.13: Overall Efficiency vs. Angle of Attack,  $V = 20$  ms, Various Throttle

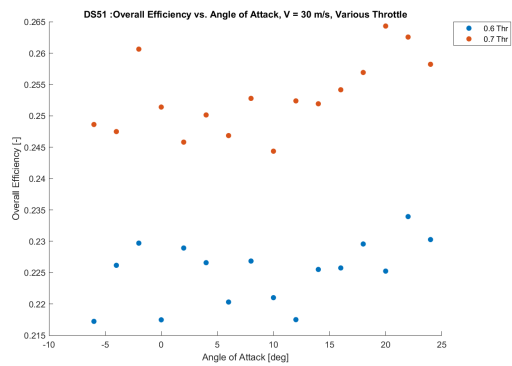


Figure B.14: Overall Efficiency vs. Angle of Attack,  $V = 30$  ms, Various Throttle

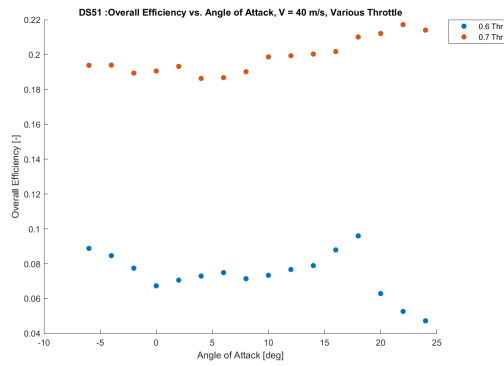


Figure B.15: Overall Efficiency vs. Angle of Attack,  $V = 40$  ms, Various Throttle

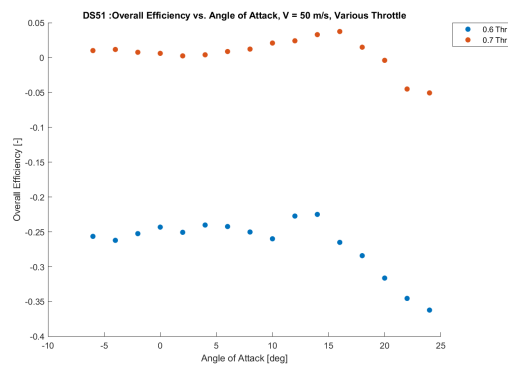


Figure B.16: Overall Efficiency vs. Angle of Attack,  $V = 50$  ms, Various Throttle

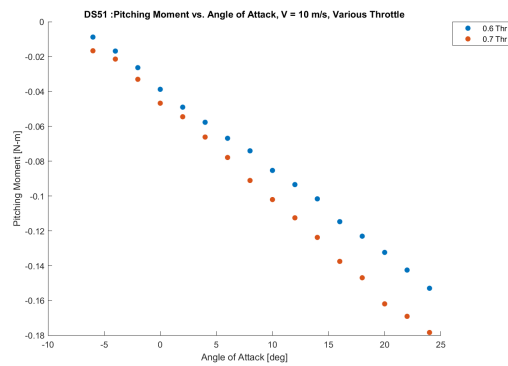


Figure B.17: Pitching Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle

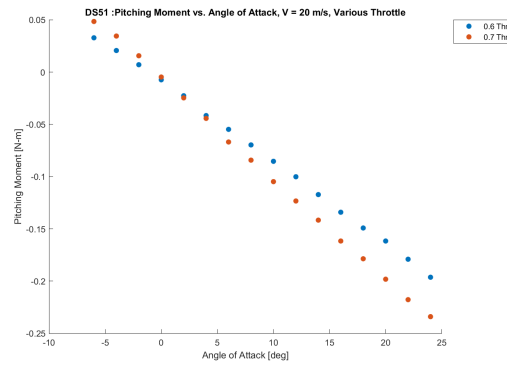


Figure B.18: Pitching Moment vs. Angle of Attack,  $V = 20$  ms, Various Throttle

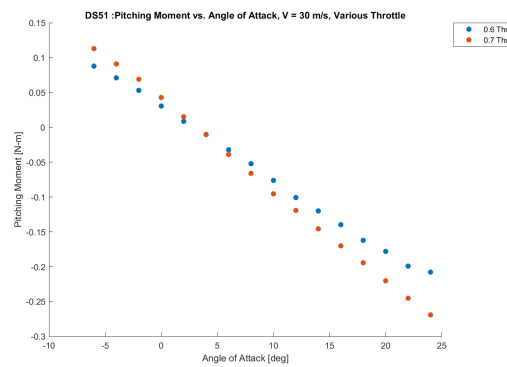


Figure B.19: Pitching Moment vs. Angle of Attack,  $V = 30$  ms, Various Throttle

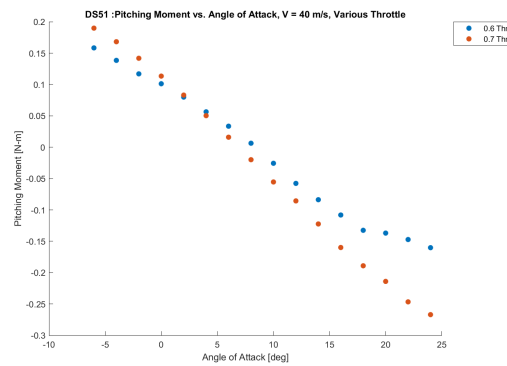


Figure B.20: Pitching Moment vs. Angle of Attack,  $V = 40$  ms, Various Throttle

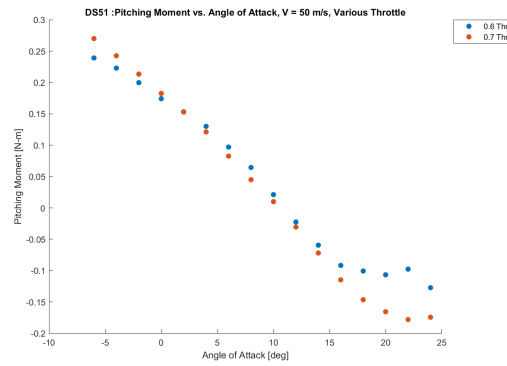


Figure B.21: Pitching Moment vs. Angle of Attack,  $V = 50$  ms, Various Throttle

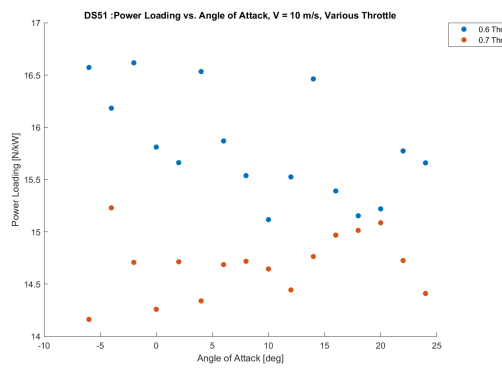


Figure B.22: Power Loading vs. Angle of Attack,  $V = 10$  ms, Various Throttle

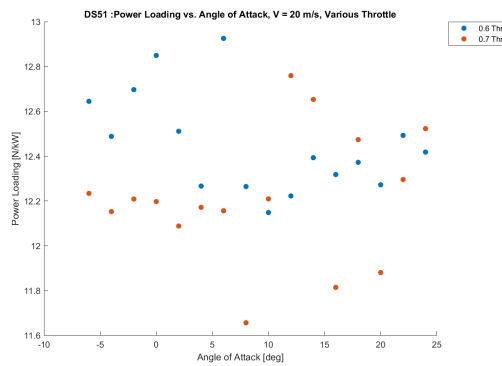


Figure B.23: Power Loading vs. Angle of Attack,  $V = 20$  ms, Various Throttle

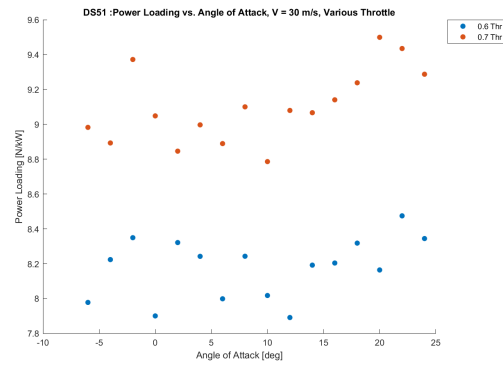


Figure B.24: Power Loading vs. Angle of Attack,  $V = 30$  ms, Various Throttle

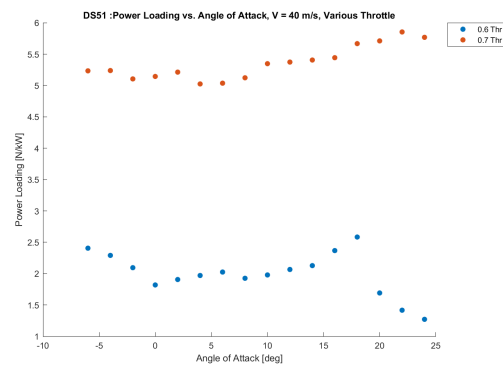


Figure B.25: Power Loading vs. Angle of Attack,  $V = 40$  ms, Various Throttle

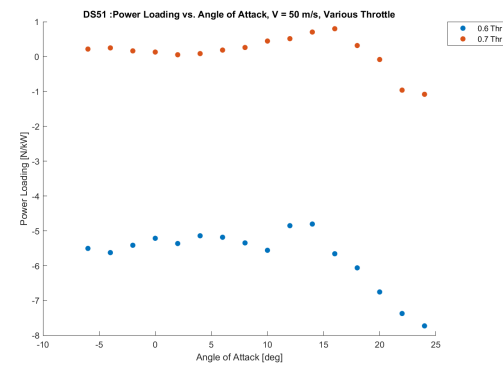


Figure B.26: Power Loading vs. Angle of Attack,  $V = 50$  ms, Various Throttle

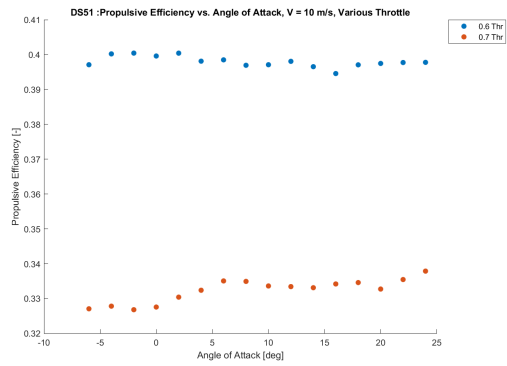


Figure B.27: Propulsive Efficiency vs. Angle of Attack, V = 10 ms, Various Throttle

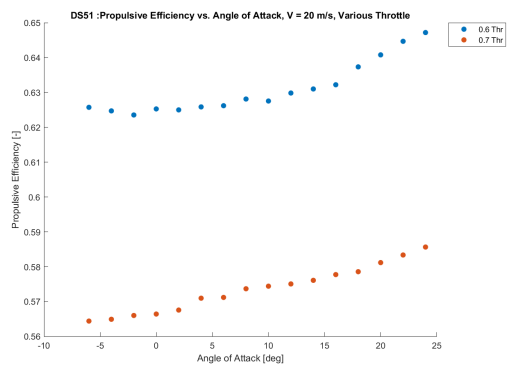


Figure B.28: Propulsive Efficiency vs. Angle of Attack, V = 20 ms, Various Throttle

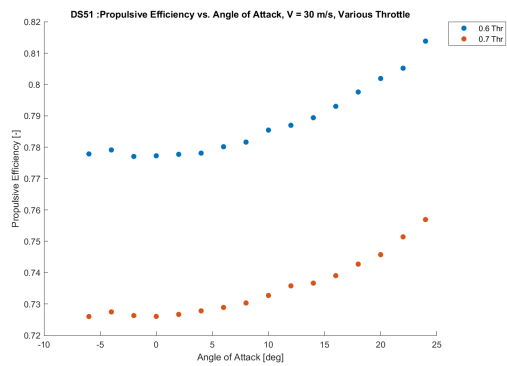


Figure B.29: Propulsive Efficiency vs. Angle of Attack, V = 30 ms, Various Throttle



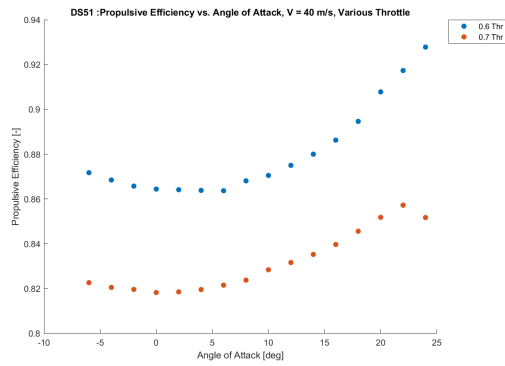


Figure B.30: Propulsive Efficiency vs. Angle of Attack,  $V = 40$  ms, Various Throttle

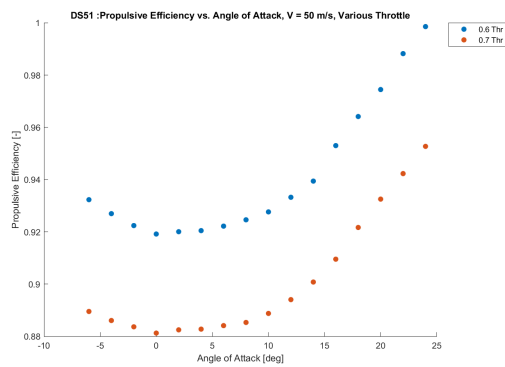


Figure B.31: Propulsive Efficiency vs. Angle of Attack,  $V = 50$  ms, Various Throttle

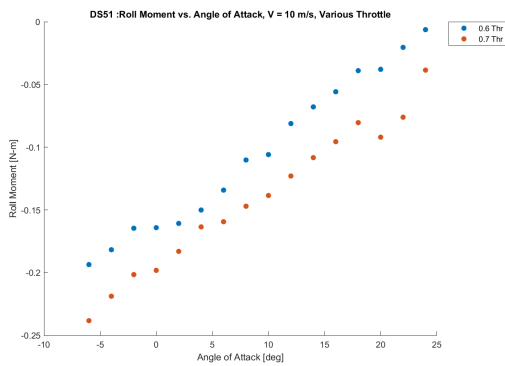


Figure B.32: Roll Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle

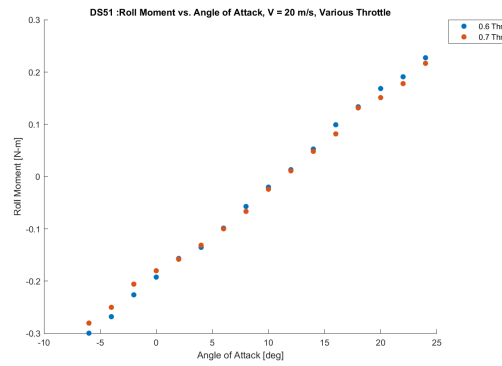


Figure B.33: Roll Moment vs. Angle of Attack,  $V = 20$  ms, Various Throttle

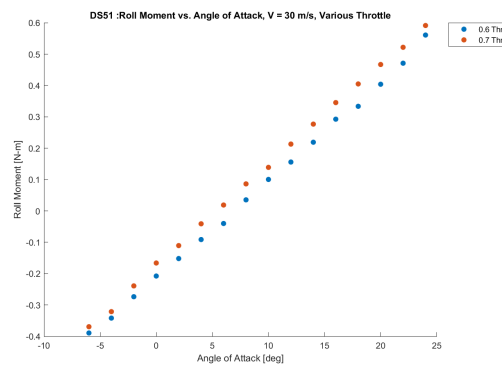


Figure B.34: Roll Moment vs. Angle of Attack,  $V = 30$  ms, Various Throttle

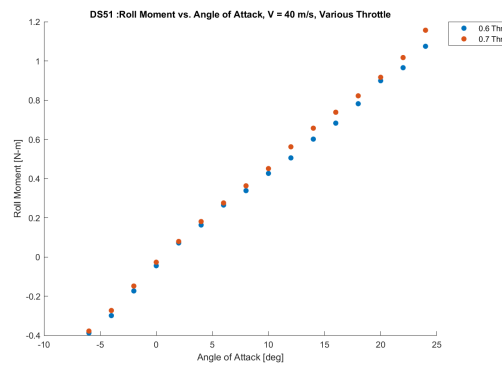


Figure B.35: Roll Moment vs. Angle of Attack,  $V = 40$  ms, Various Throttle

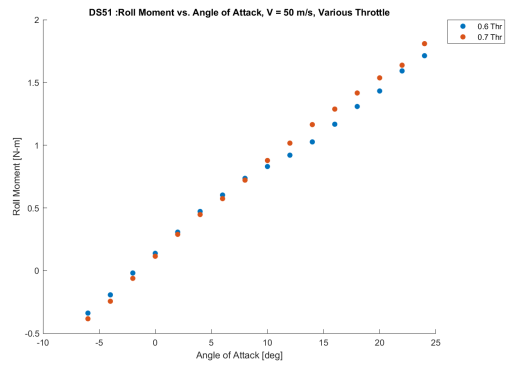


Figure B.36: Roll Moment vs. Angle of Attack, V = 50 ms, Various Throttle

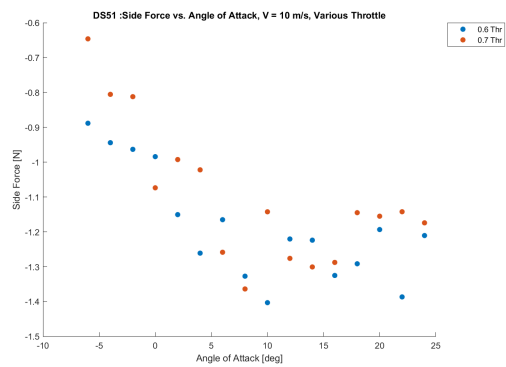


Figure B.37: Side Force vs. Angle of Attack, V = 10 ms, Various Throttle

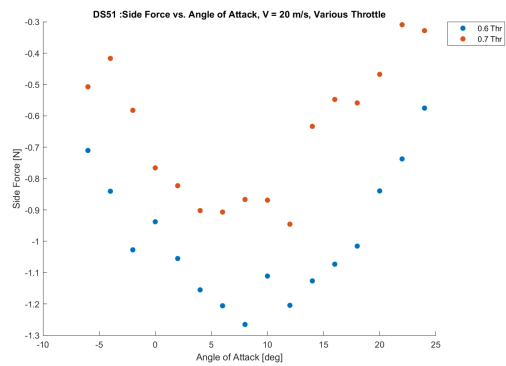


Figure B.38: Side Force vs. Angle of Attack, V = 20 ms, Various Throttle

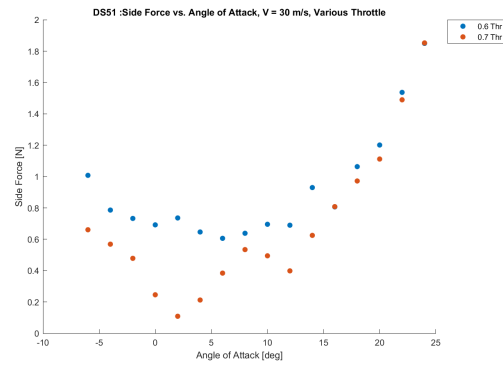


Figure B.39: Side Force vs. Angle of Attack,  $V = 30$  ms, Various Throttle

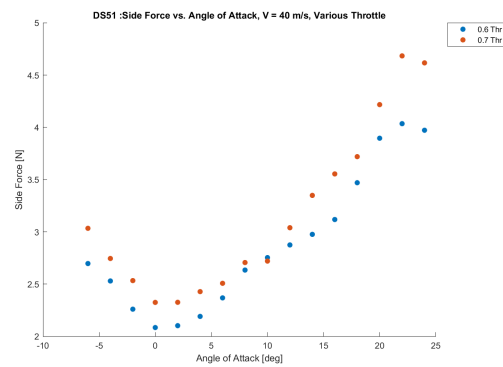


Figure B.40: Side Force vs. Angle of Attack,  $V = 40$  ms, Various Throttle

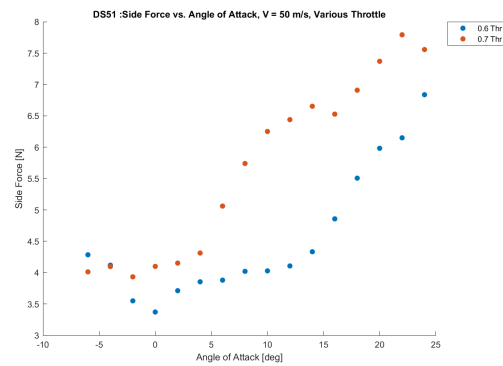


Figure B.41: Side Force vs. Angle of Attack,  $V = 50$  ms, Various Throttle

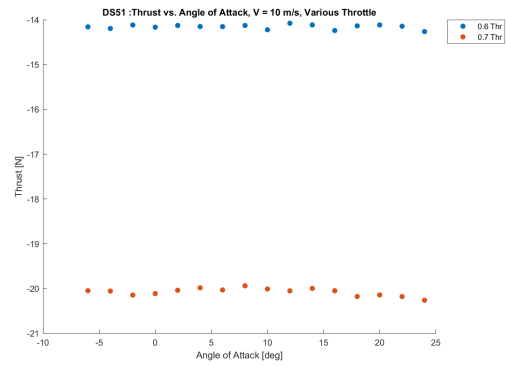


Figure B.42: Thrust vs. Angle of Attack,  $V = 10$  ms, Various Throttle

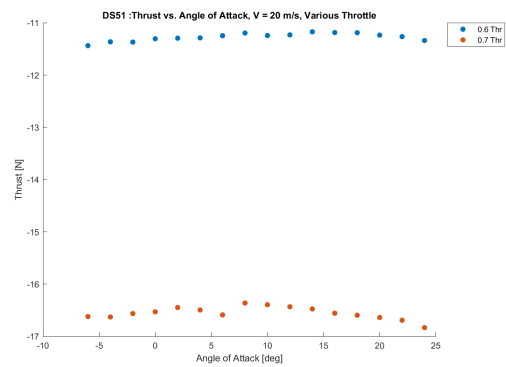


Figure B.43: Thrust vs. Angle of Attack,  $V = 20$  ms, Various Throttle

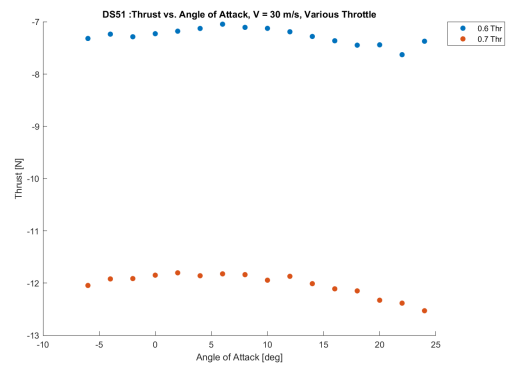


Figure B.44: Thrust vs. Angle of Attack,  $V = 30$  ms, Various Throttle

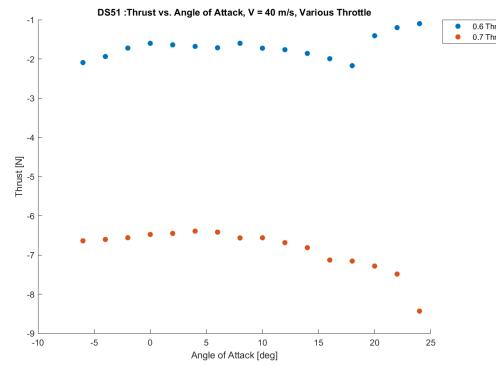


Figure B.45: Thrust vs. Angle of Attack,  $V = 40$  ms, Various Throttle

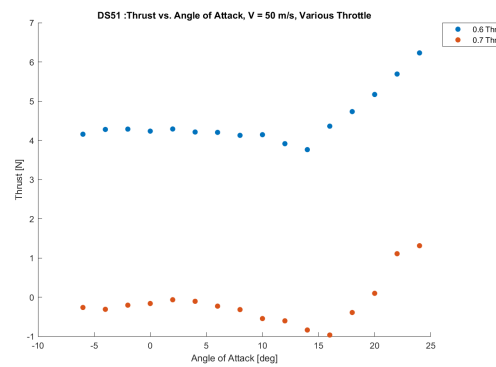


Figure B.46: Thrust vs. Angle of Attack,  $V = 50$  ms, Various Throttle

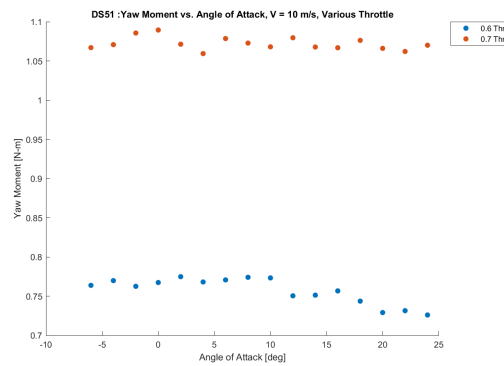


Figure B.47: Yaw Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle

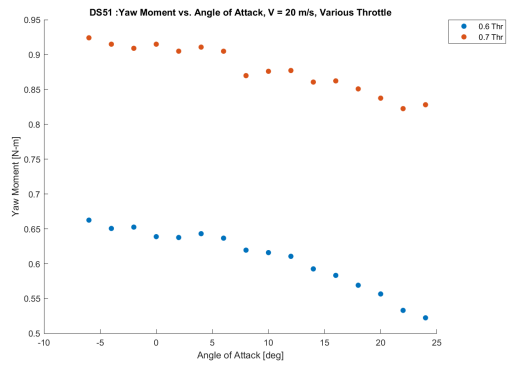


Figure B.48: Yaw Moment vs. Angle of Attack,  $V = 20$  ms, Various Throttle

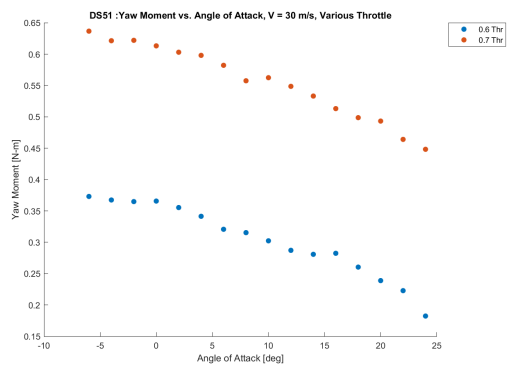


Figure B.49: Yaw Moment vs. Angle of Attack,  $V = 30$  ms, Various Throttle

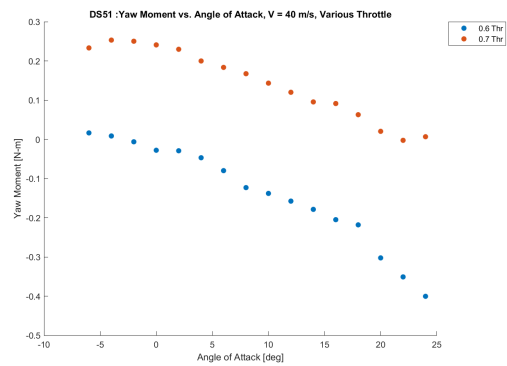


Figure B.50: Yaw Moment vs. Angle of Attack,  $V = 40$  ms, Various Throttle

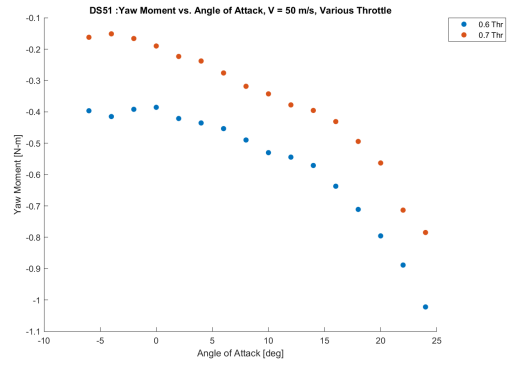


Figure B.51: Yaw Moment vs. Angle of Attack,  $V = 50$  ms, Various Throttle

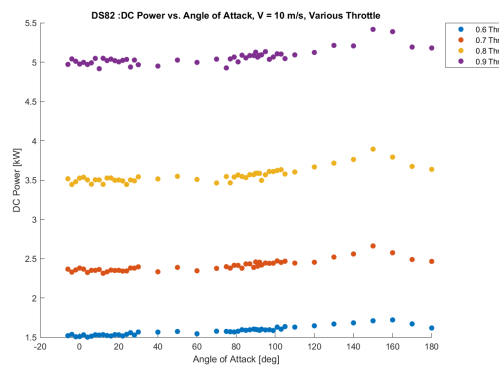


Figure B.52: DC Power vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all



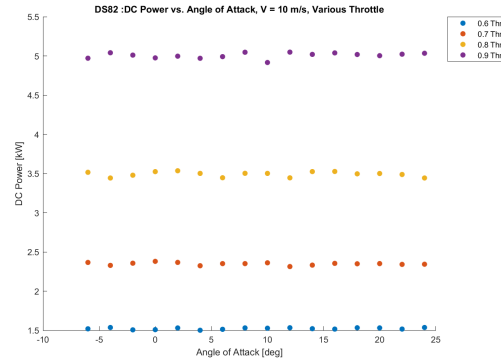


Figure B.53: DC Power vs. Angle of Attack, V = 10 ms, Various Throttle

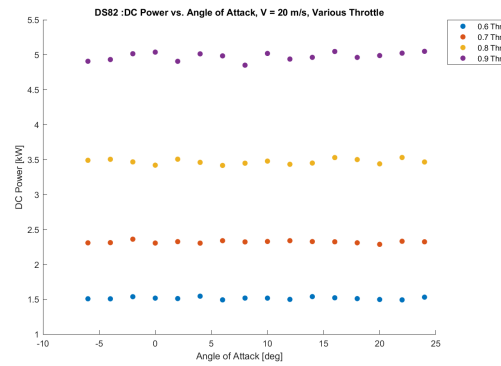


Figure B.54: DC Power vs. Angle of Attack, V = 20 ms, Various Throttle

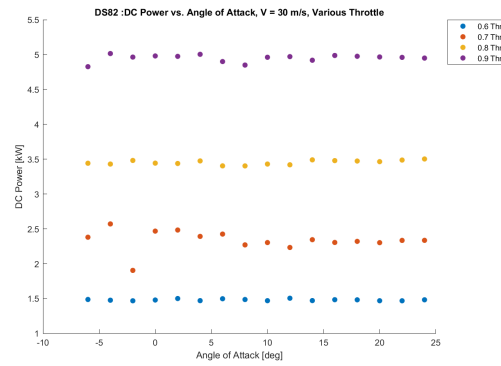


Figure B.55: DC Power vs. Angle of Attack,  $V = 30$  ms, Various Throttle

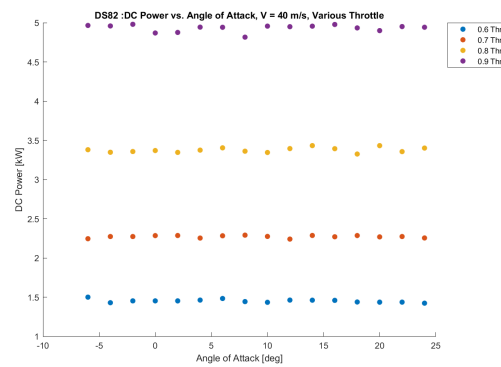


Figure B.56: DC Power vs. Angle of Attack,  $V = 40$  ms, Various Throttle

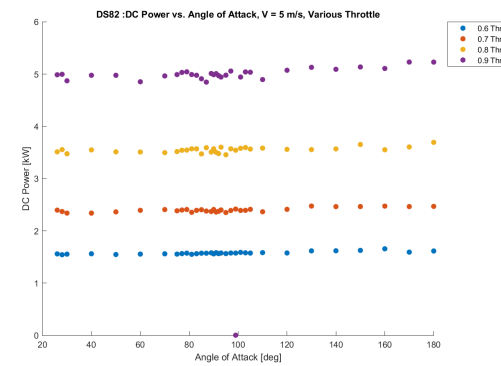


Figure B.57: DC Power vs. Angle of Attack,  $V = 5$  ms, Various Throttle,all

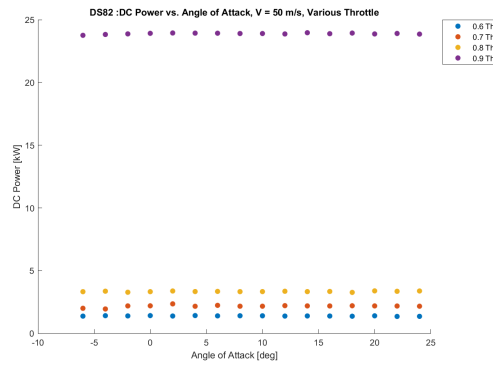


Figure B.58: DC Power vs. Angle of Attack,  $V = 50$  ms, Various Throttle

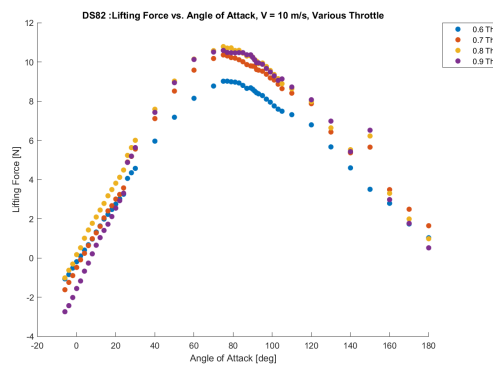


Figure B.59: Lifting Force vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all

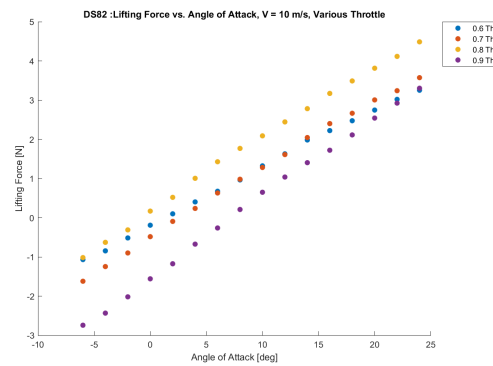


Figure B.60: Lifting Force vs. Angle of Attack,  $V = 10$  ms, Various Throttle

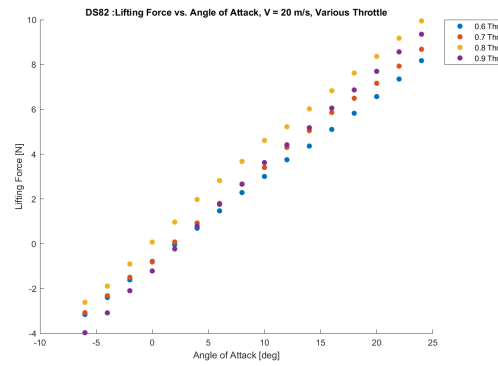


Figure B.61: Lifting Force vs. Angle of Attack,  $V = 20$  ms, Various Throttle

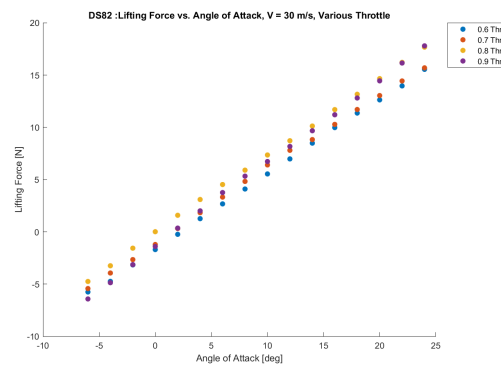


Figure B.62: Lifting Force vs. Angle of Attack,  $V = 30$  ms, Various Throttle

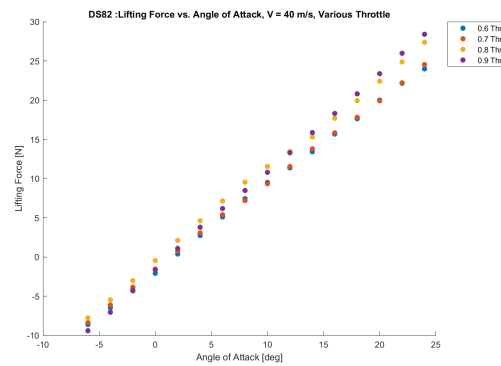


Figure B.63: Lifting Force vs. Angle of Attack,  $V = 40$  ms, Various Throttle

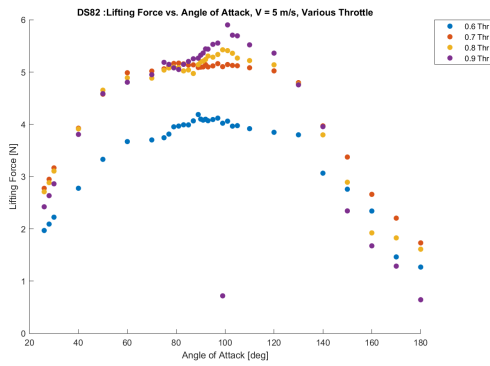


Figure B.64: Lifting Force vs. Angle of Attack,  $V = 5$  ms, Various Throttle,all

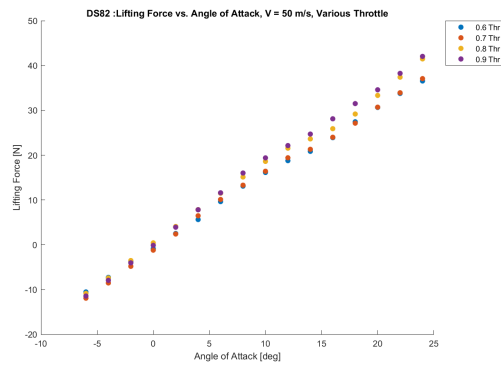


Figure B.65: Lifting Force vs. Angle of Attack,  $V = 50$  ms, Various Throttle

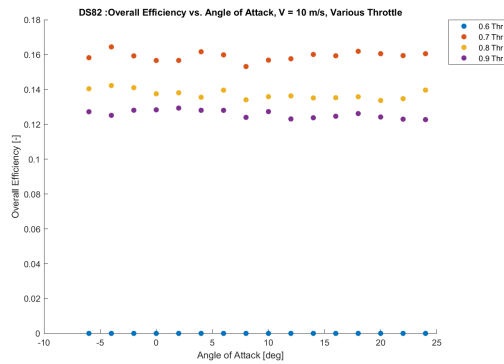


Figure B.66: Overall Efficiency vs. Angle of Attack,  $V = 10$  ms, Various Throttle

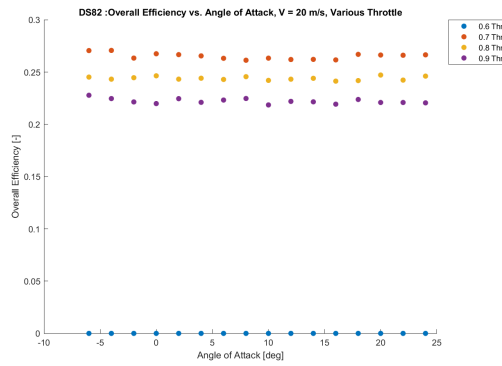


Figure B.67: Overall Efficiency vs. Angle of Attack,  $V = 20$  ms, Various Throttle

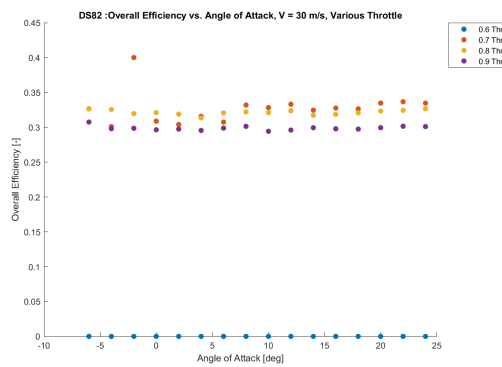


Figure B.68: Overall Efficiency vs. Angle of Attack,  $V = 30$  ms, Various Throttle

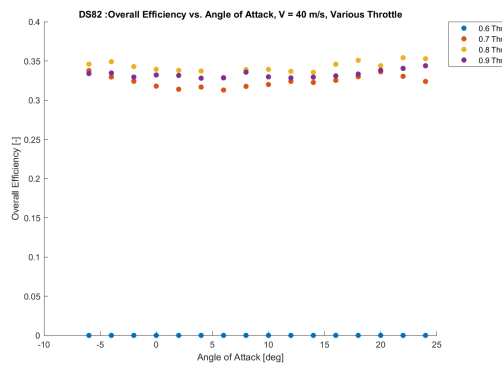


Figure B.69: Overall Efficiency vs. Angle of Attack,  $V = 40$  ms, Various Throttle

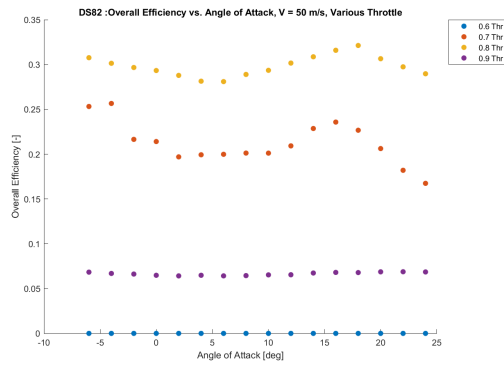


Figure B.70: Overall Efficiency vs. Angle of Attack, V = 50 ms, Various Throttle

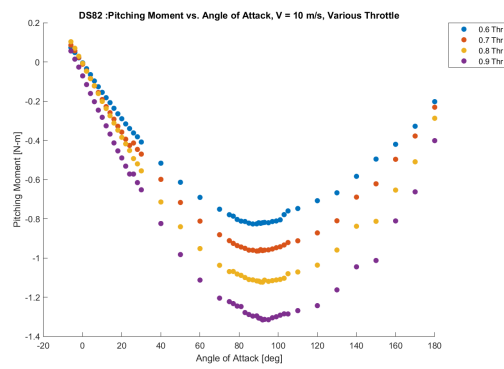


Figure B.71: Pitching Moment vs. Angle of Attack, V = 10 ms, Various Throttle,all

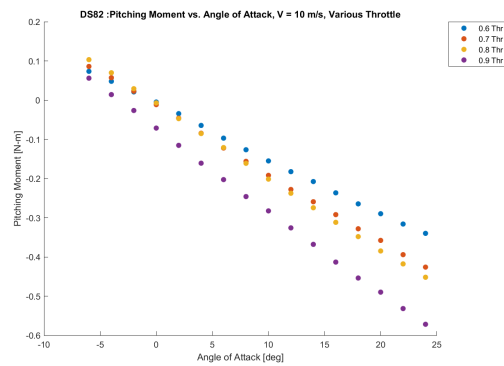


Figure B.72: Pitching Moment vs. Angle of Attack, V = 10 ms, Various Throttle

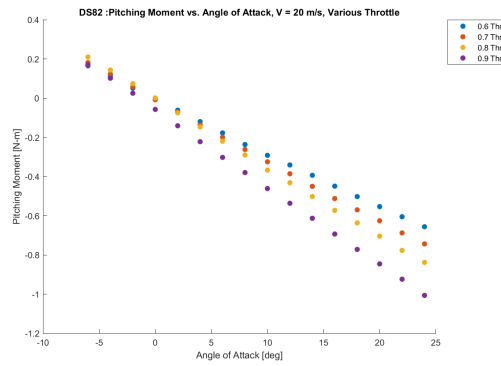


Figure B.73: Pitching Moment vs. Angle of Attack, V = 20 ms, Various Throttle

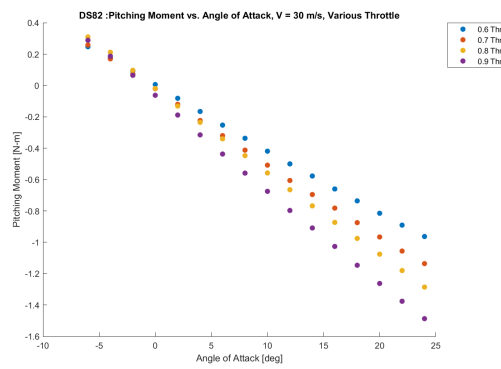


Figure B.74: Pitching Moment vs. Angle of Attack, V = 30 ms, Various Throttle

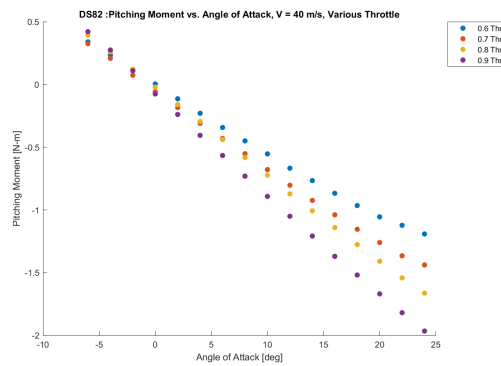


Figure B.75: Pitching Moment vs. Angle of Attack, V = 40 ms, Various Throttle



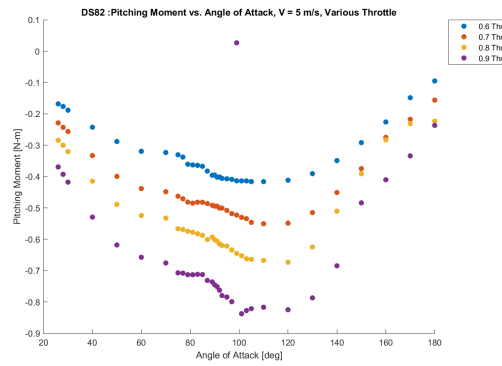


Figure B.76: Pitching Moment vs. Angle of Attack,  $V = 5$  ms, Various Throttle,all

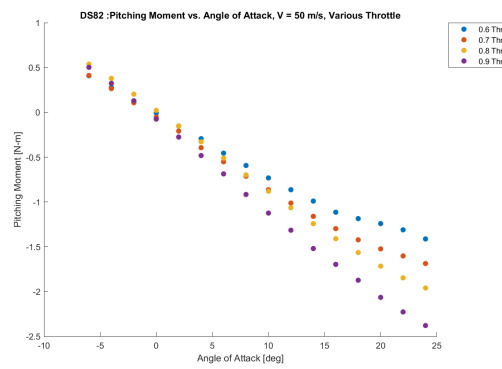


Figure B.77: Pitching Moment vs. Angle of Attack,  $V = 50$  ms, Various Throttle

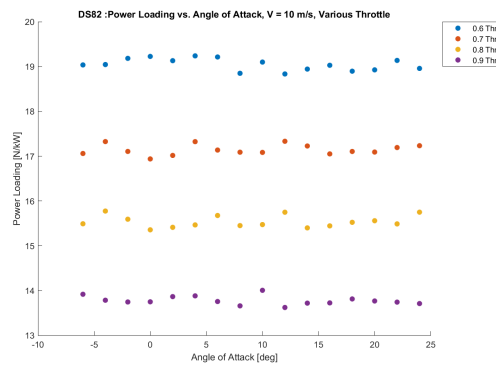


Figure B.78: Power Loading vs. Angle of Attack,  $V = 10$  ms, Various Throttle

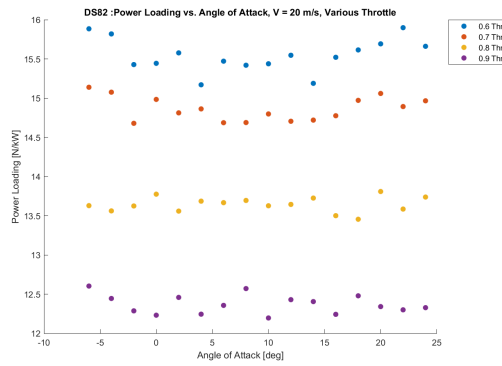


Figure B.79: Power Loading vs. Angle of Attack,  $V = 20$  ms, Various Throttle

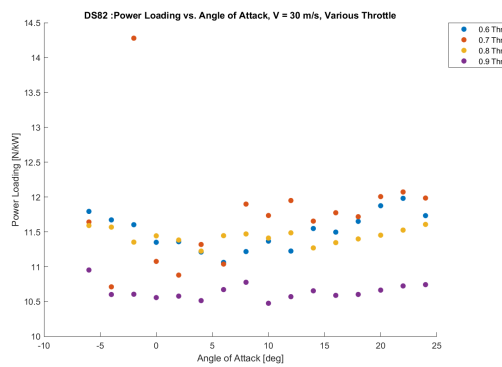


Figure B.80: Power Loading vs. Angle of Attack,  $V = 30$  ms, Various Throttle

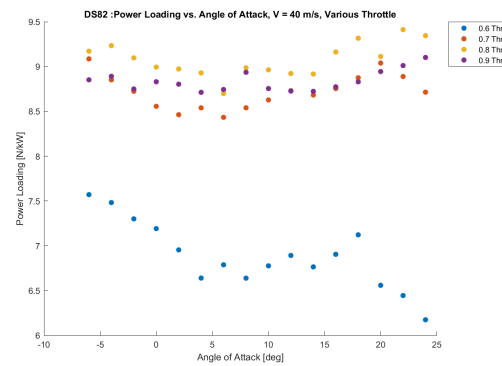


Figure B.81: Power Loading vs. Angle of Attack,  $V = 40$  ms, Various Throttle

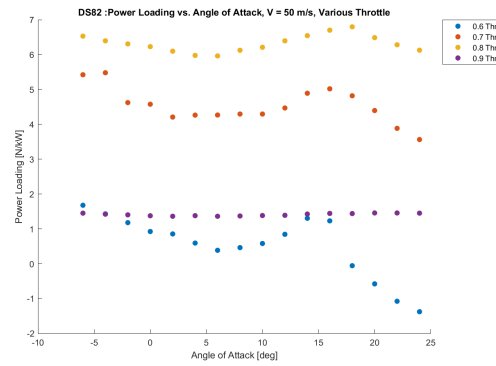


Figure B.82: Power Loading vs. Angle of Attack,  $V = 50$  ms, Various Throttle

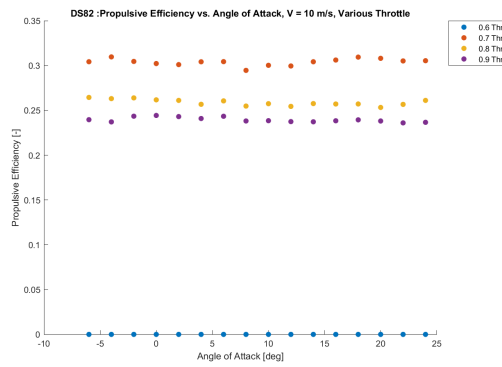


Figure B.83: Propulsive Efficiency vs. Angle of Attack,  $V = 10$  ms, Various Throttle

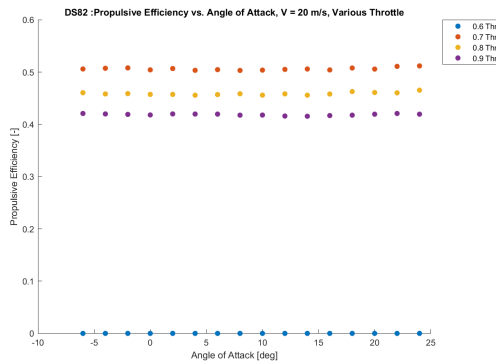


Figure B.84: Propulsive Efficiency vs. Angle of Attack,  $V = 20$  ms, Various Throttle

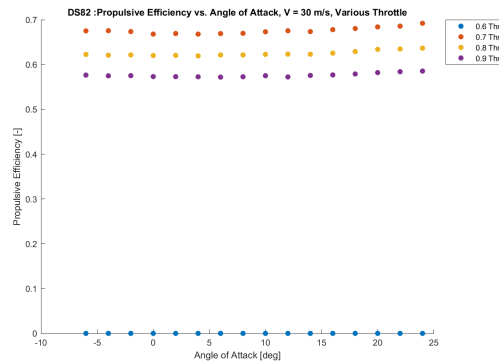


Figure B.85: Propulsive Efficiency vs. Angle of Attack,  $V = 30$  ms, Various Throttle

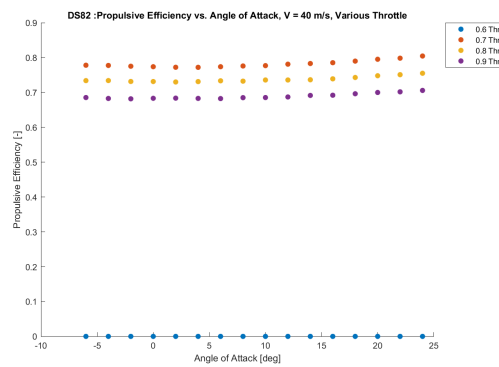


Figure B.86: Propulsive Efficiency vs. Angle of Attack,  $V = 40$  ms, Various Throttle

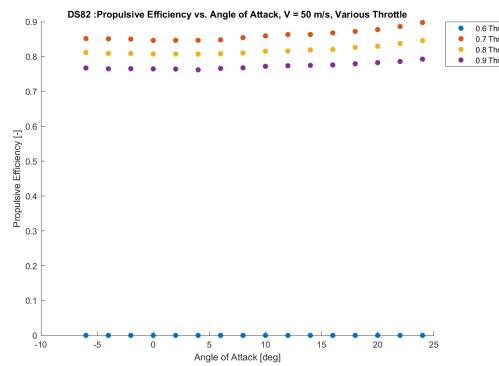


Figure B.87: Propulsive Efficiency vs. Angle of Attack,  $V = 50$  ms, Various Throttle



Figure B.88: Roll Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all

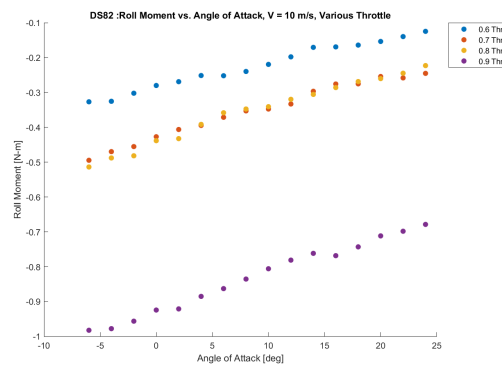


Figure B.89: Roll Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle

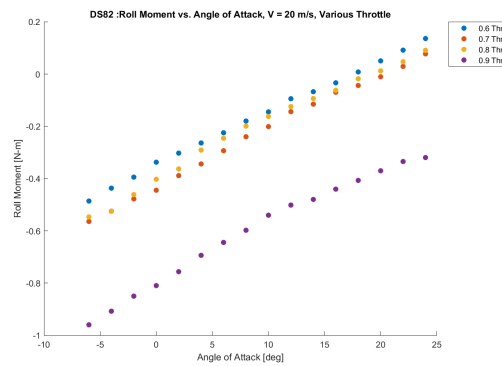


Figure B.90: Roll Moment vs. Angle of Attack,  $V = 20$  ms, Various Throttle

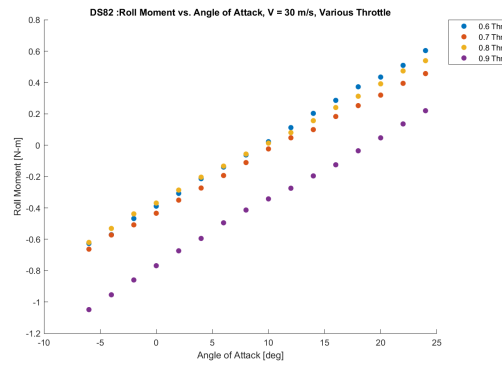


Figure B.91: Roll Moment vs. Angle of Attack,  $V = 30$  ms, Various Throttle

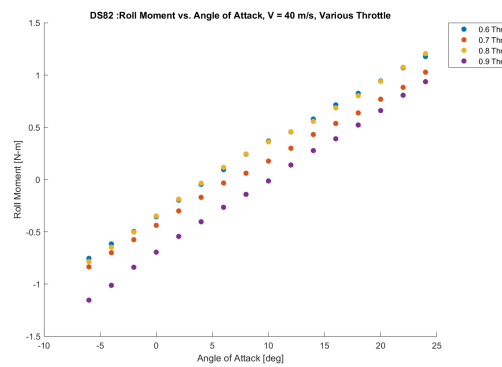


Figure B.92: Roll Moment vs. Angle of Attack,  $V = 40$  ms, Various Throttle

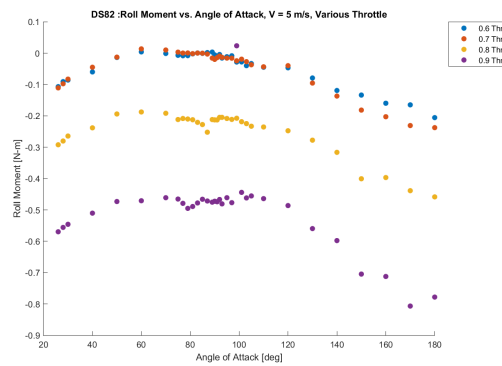


Figure B.93: Roll Moment vs. Angle of Attack,  $V = 5$  ms, Various Throttle,all

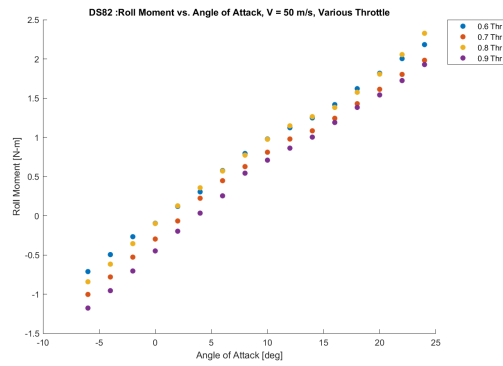


Figure B.94: Roll Moment vs. Angle of Attack,  $V = 50$  ms, Various Throttle

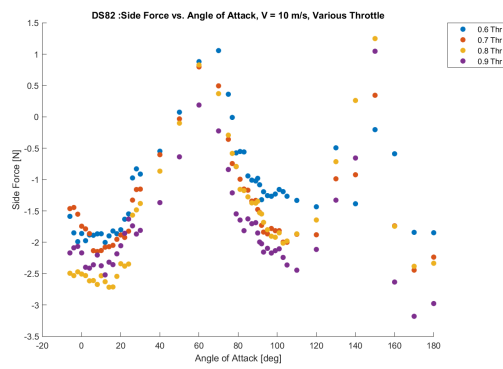


Figure B.95: Side Force vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all

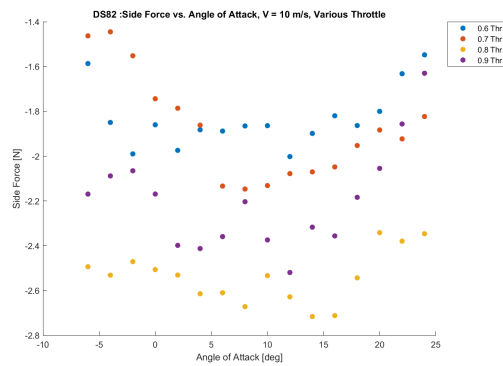


Figure B.96: Side Force vs. Angle of Attack,  $V = 10$  ms, Various Throttle

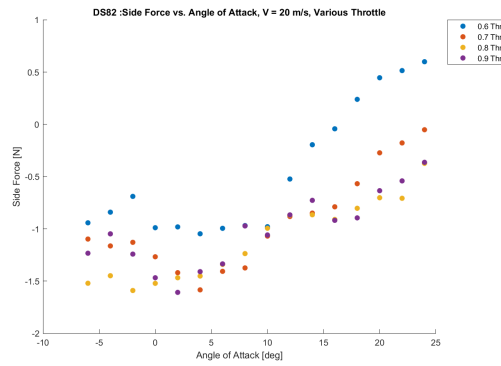


Figure B.97: Side Force vs. Angle of Attack,  $V = 20$  ms, Various Throttle

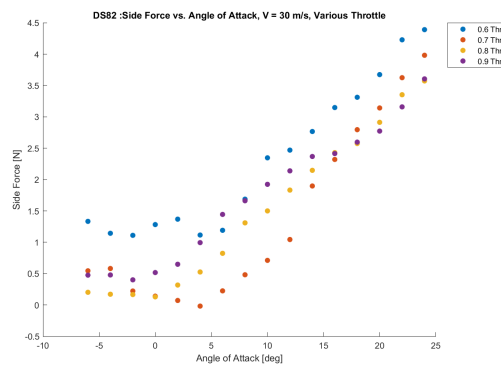


Figure B.98: Side Force vs. Angle of Attack,  $V = 30$  ms, Various Throttle

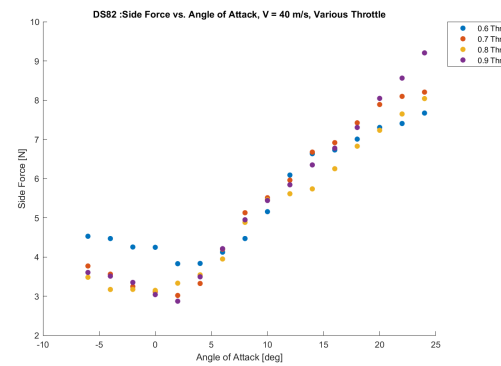


Figure B.99: Side Force vs. Angle of Attack,  $V = 40$  ms, Various Throttle



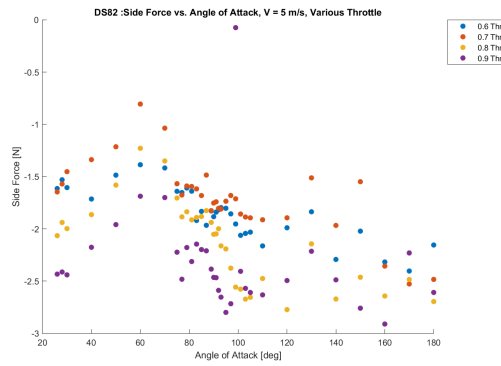


Figure B.100: Side Force vs. Angle of Attack, V = 5 ms, Various Throttle,all

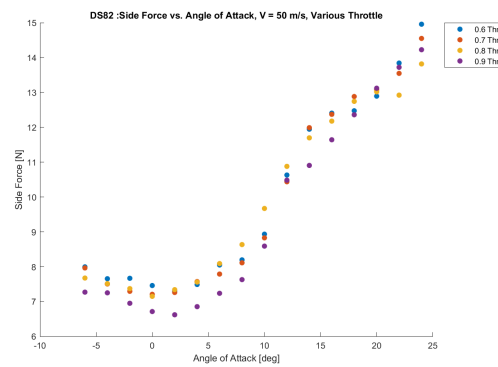


Figure B.101: Side Force vs. Angle of Attack, V = 50 ms, Various Throttle

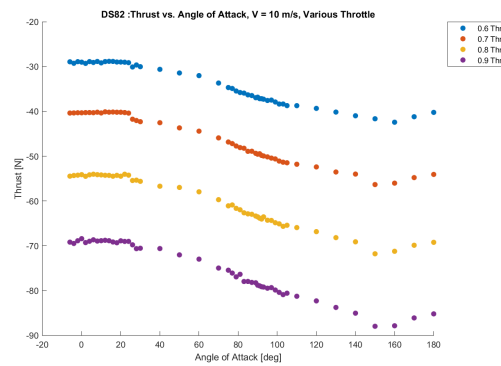


Figure B.102: Thrust vs. Angle of Attack, V = 10 ms, Various Throttle,all

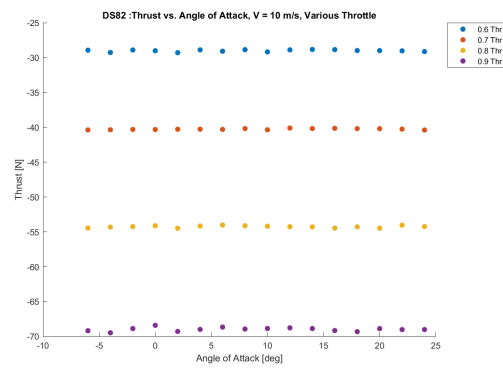


Figure B.103: Thrust vs. Angle of Attack, V = 10 ms, Various Throttle

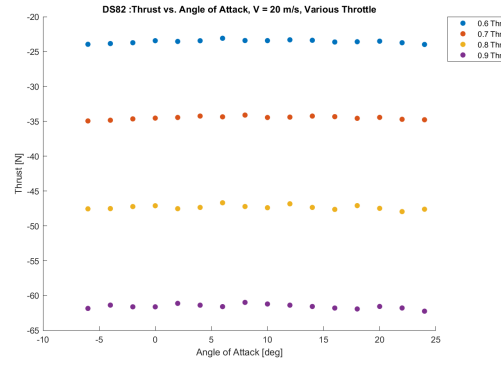


Figure B.104: Thrust vs. Angle of Attack,  $V = 20$  ms, Various Throttle

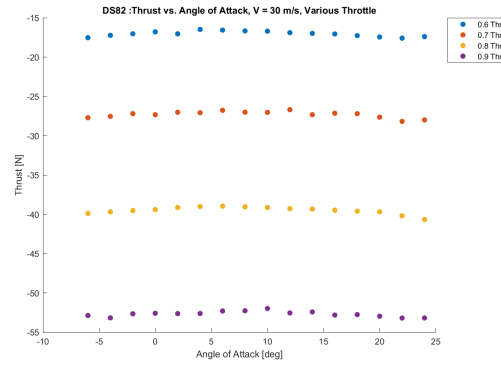


Figure B.105: Thrust vs. Angle of Attack,  $V = 30$  ms, Various Throttle

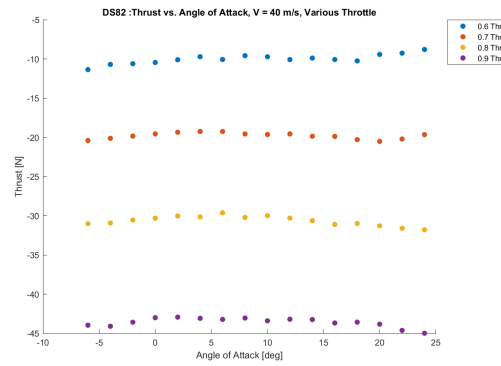


Figure B.106: Thrust vs. Angle of Attack,  $V = 40$  ms, Various Throttle

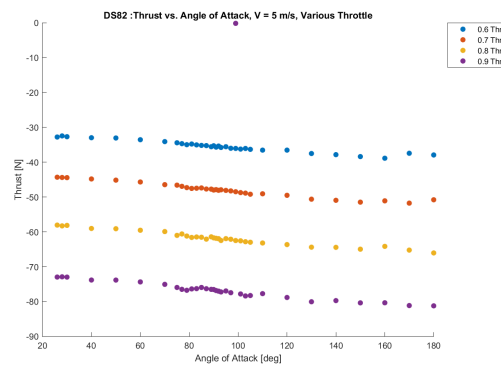


Figure B.107: Thrust vs. Angle of Attack,  $V = 5$  ms, Various Throttle,all

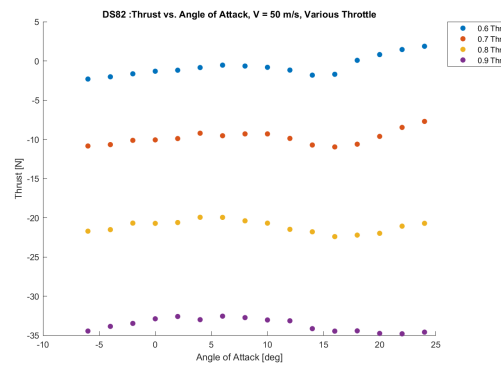


Figure B.108: Thrust vs. Angle of Attack,  $V = 50$  ms, Various Throttle

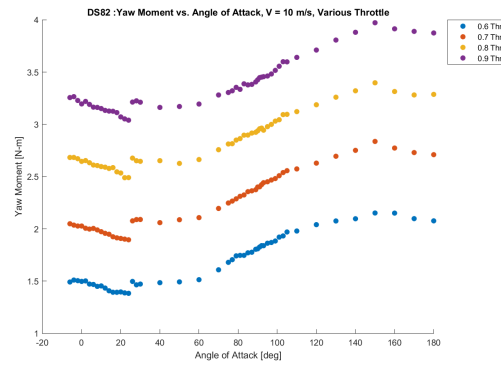


Figure B.109: Yaw Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all

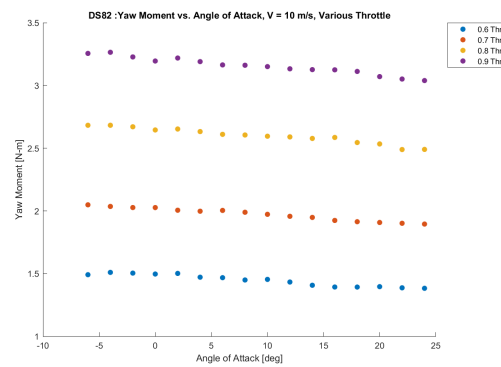


Figure B.110: Yaw Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle

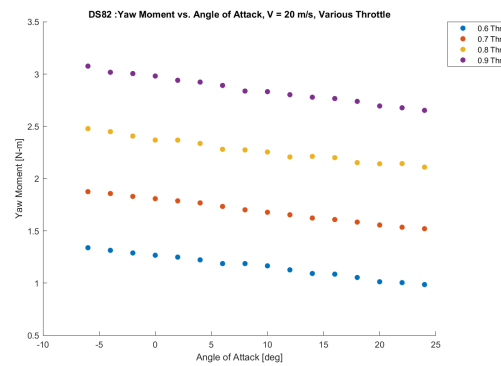


Figure B.111: Yaw Moment vs. Angle of Attack,  $V = 20$  ms, Various Throttle

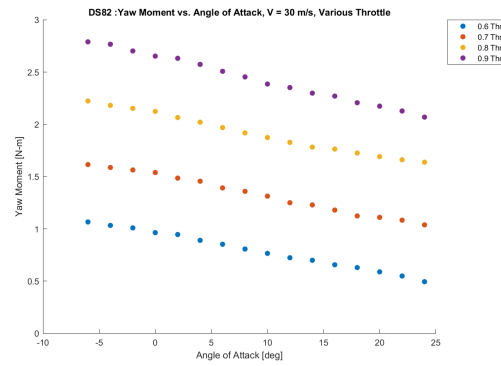


Figure B.112: Yaw Moment vs. Angle of Attack, V = 30 ms, Various Throttle

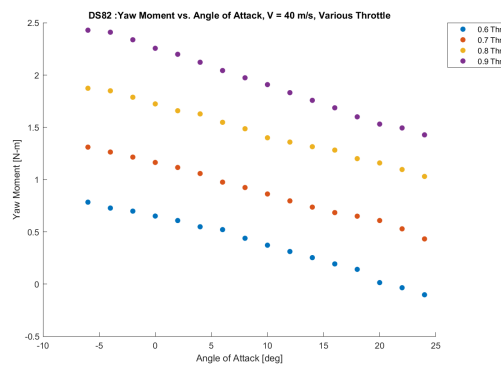


Figure B.113: Yaw Moment vs. Angle of Attack, V = 40 ms, Various Throttle

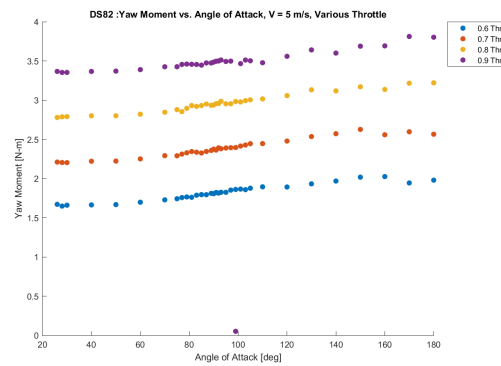


Figure B.114: Yaw Moment vs. Angle of Attack, V = 5 ms, Various Throttle,all

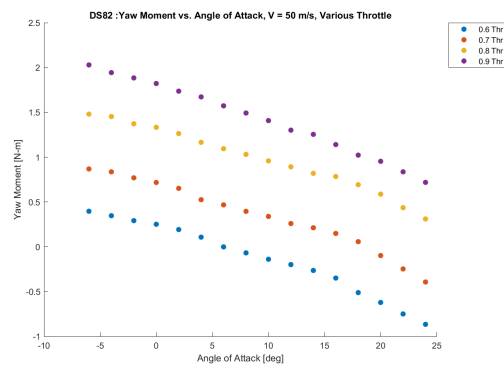


Figure B.115: Yaw Moment vs. Angle of Attack, V = 50 ms, Various Throttle

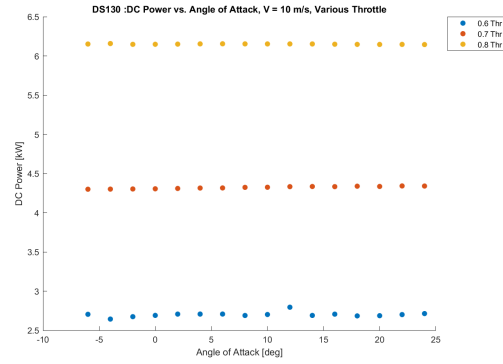


Figure B.116: DC Power vs. Angle of Attack, V = 10 ms, Various Throttle

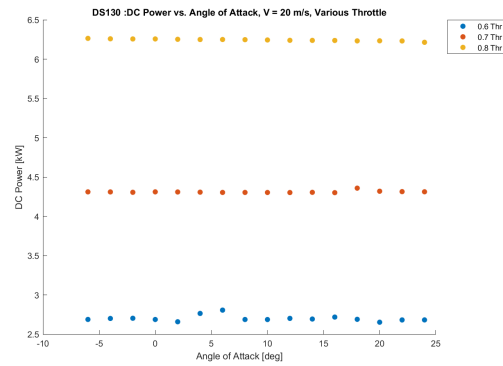


Figure B.117: DC Power vs. Angle of Attack, V = 20 ms, Various Throttle

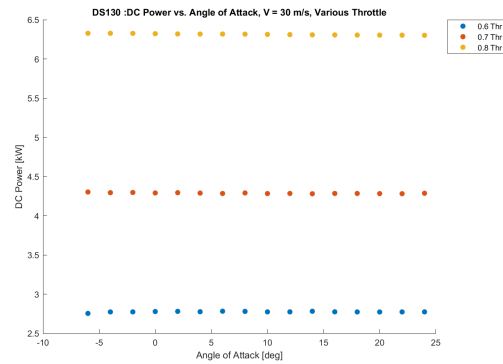


Figure B.118: DC Power vs. Angle of Attack, V = 30 ms, Various Throttle



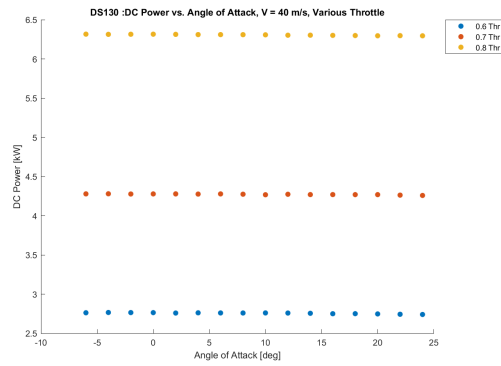


Figure B.119: DC Power vs. Angle of Attack, V = 40 ms, Various Throttle

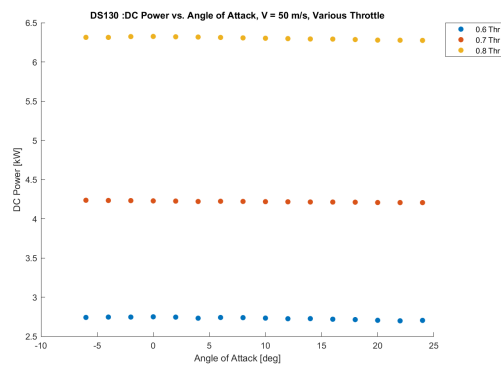


Figure B.120: DC Power vs. Angle of Attack, V = 50 ms, Various Throttle

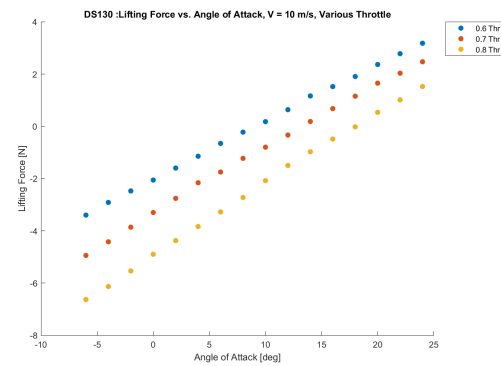


Figure B.121: Lifting Force vs. Angle of Attack, V = 10 ms, Various Throttle

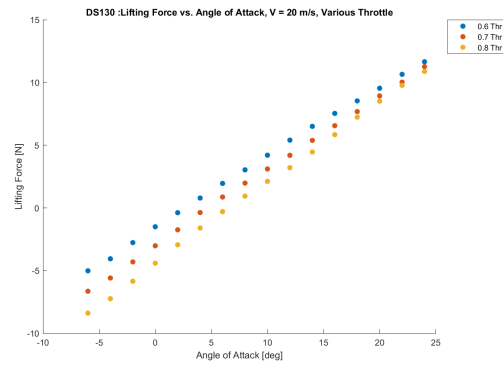


Figure B.122: Lifting Force vs. Angle of Attack, V = 20 ms, Various Throttle

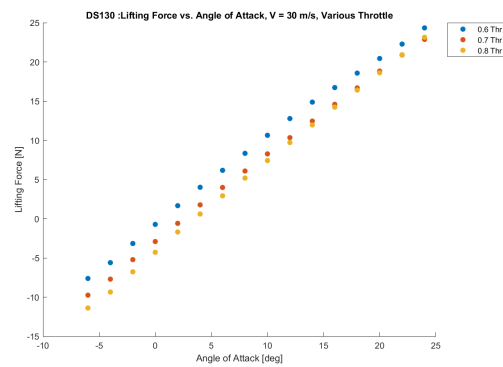


Figure B.123: Lifting Force vs. Angle of Attack, V = 30 ms, Various Throttle

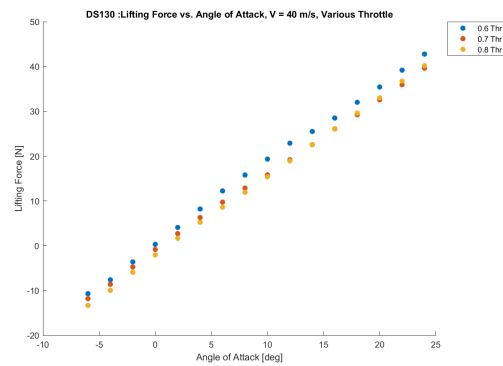


Figure B.124: Lifting Force vs. Angle of Attack, V = 40 ms, Various Throttle

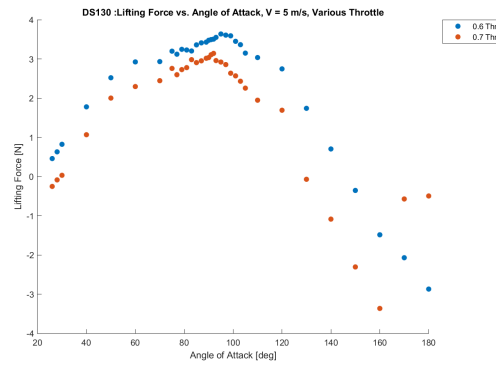


Figure B.125: Lifting Force vs. Angle of Attack, V = 5 ms, Various Throttle,all

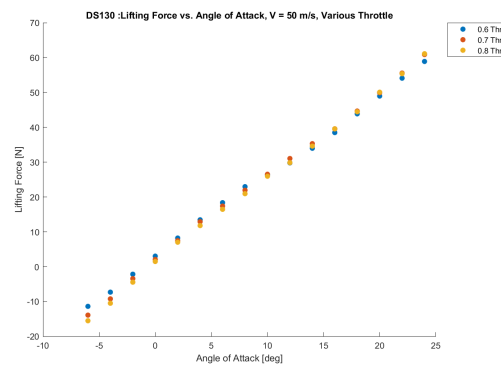


Figure B.126: Lifting Force vs. Angle of Attack, V = 50 ms, Various Throttle

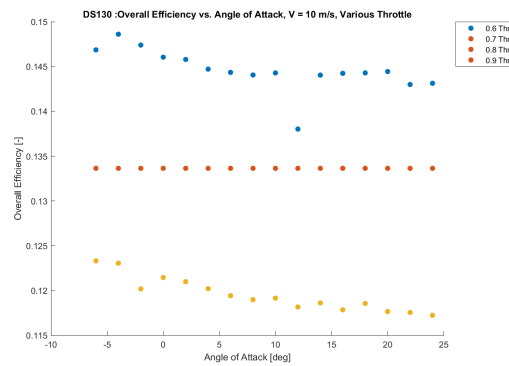


Figure B.127: Overall Efficiency vs. Angle of Attack, V = 10 ms, Various Throttle

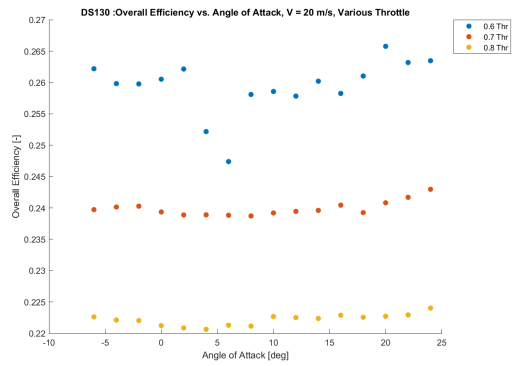


Figure B.128: Overall Efficiency vs. Angle of Attack,  $V = 20$  ms, Various Throttle

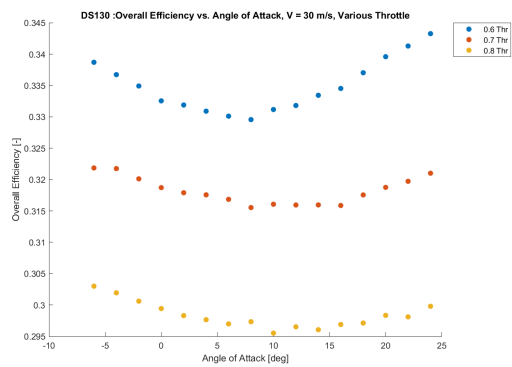


Figure B.129: Overall Efficiency vs. Angle of Attack,  $V = 30$  ms, Various Throttle

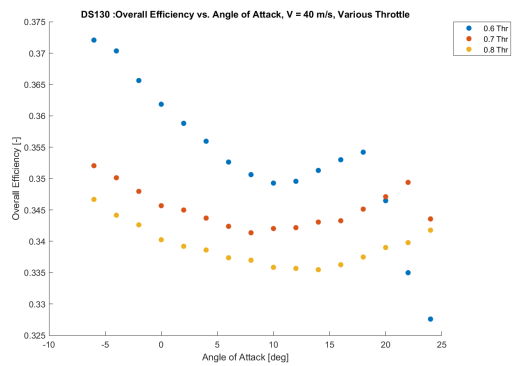


Figure B.130: Overall Efficiency vs. Angle of Attack,  $V = 40$  ms, Various Throttle

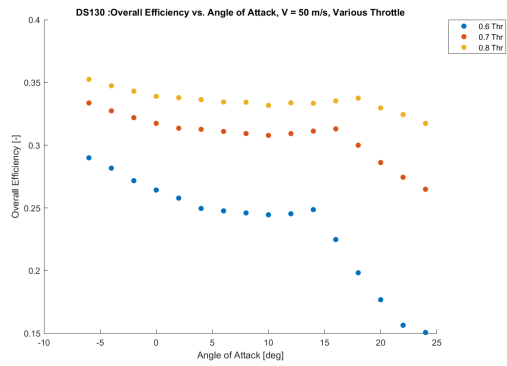


Figure B.131: Overall Efficiency vs. Angle of Attack,  $V = 50$  ms, Various Throttle

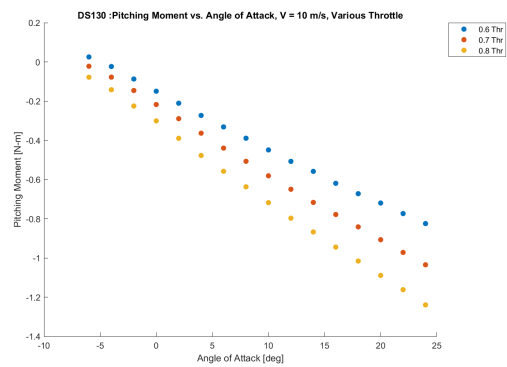


Figure B.132: Pitching Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle

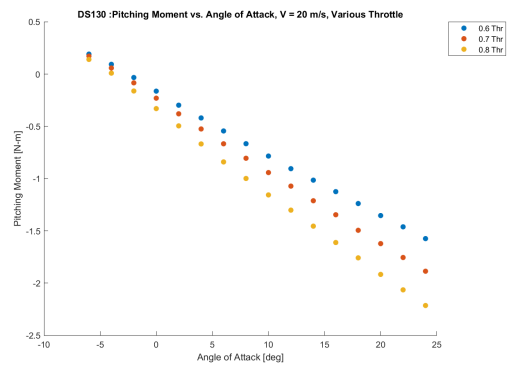


Figure B.133: Pitching Moment vs. Angle of Attack,  $V = 20$  ms, Various Throttle

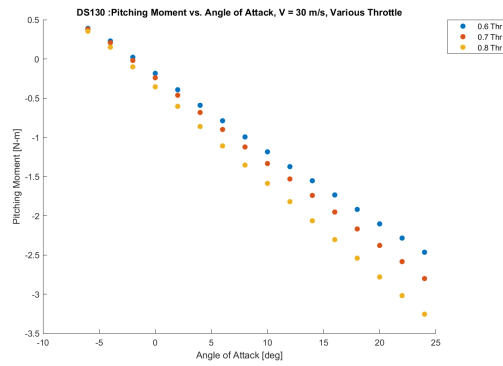


Figure B.134: Pitching Moment vs. Angle of Attack,  $V = 30$  ms, Various Throttle

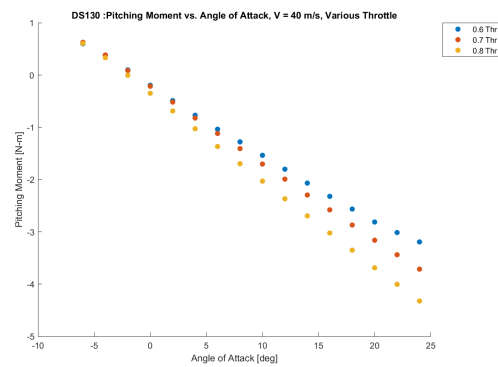


Figure B.135: Pitching Moment vs. Angle of Attack,  $V = 40$  ms, Various Throttle

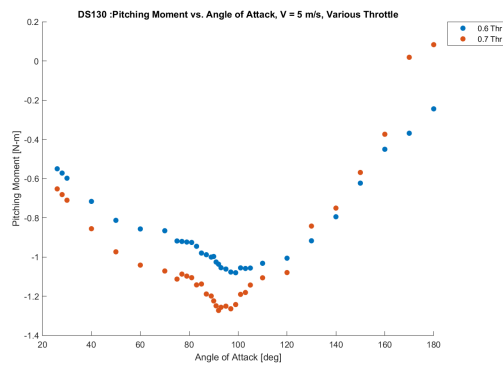


Figure B.136: Pitching Moment vs. Angle of Attack,  $V = 5$  ms, Various Throttle,all

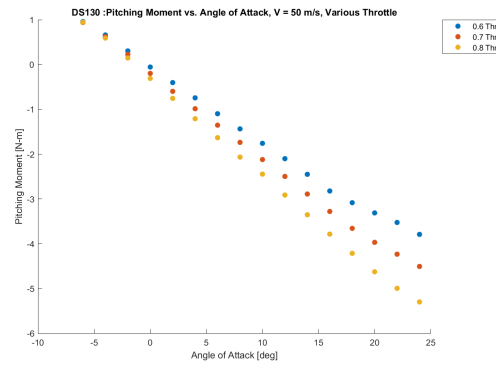


Figure B.137: Pitching Moment vs. Angle of Attack,  $V = 50$  ms, Various Throttle

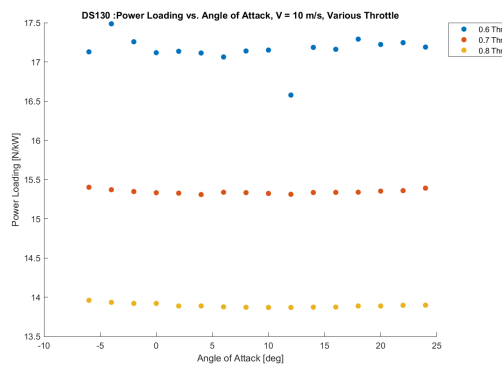


Figure B.138: Power Loading vs. Angle of Attack,  $V = 10$  ms, Various Throttle

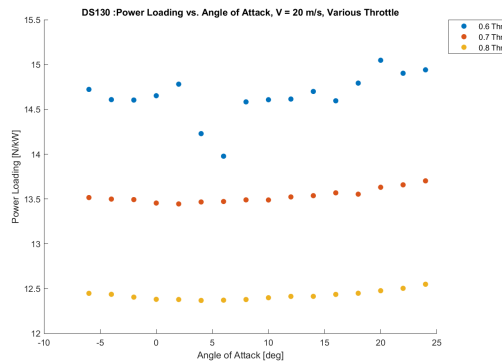


Figure B.139: Power Loading vs. Angle of Attack,  $V = 20$  ms, Various Throttle

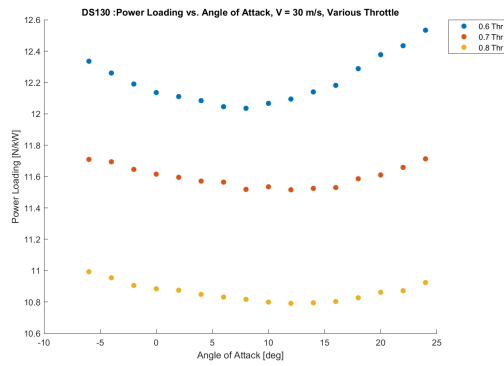


Figure B.140: Power Loading vs. Angle of Attack, V = 30 ms, Various Throttle

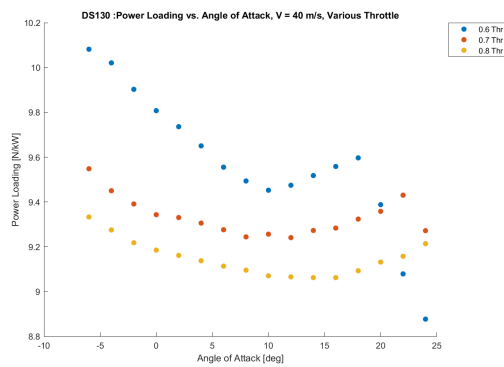


Figure B.141: Power Loading vs. Angle of Attack, V = 40 ms, Various Throttle

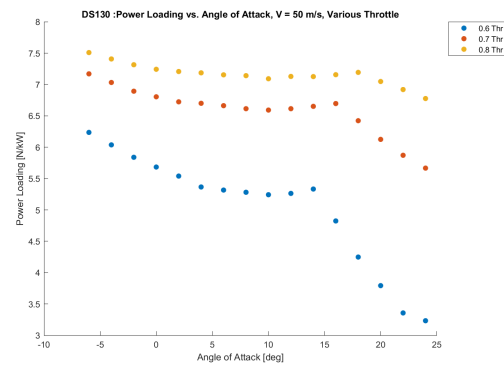


Figure B.142: Power Loading vs. Angle of Attack, V = 50 ms, Various Throttle



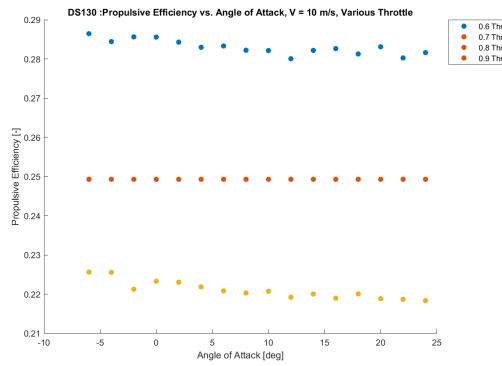


Figure B.143: Propulsive Efficiency vs. Angle of Attack, V = 10 ms, Various Throttle

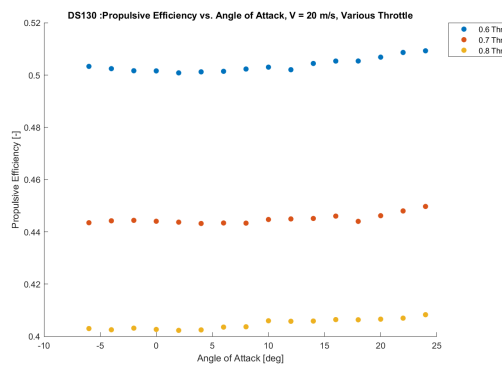


Figure B.144: Propulsive Efficiency vs. Angle of Attack, V = 20 ms, Various Throttle

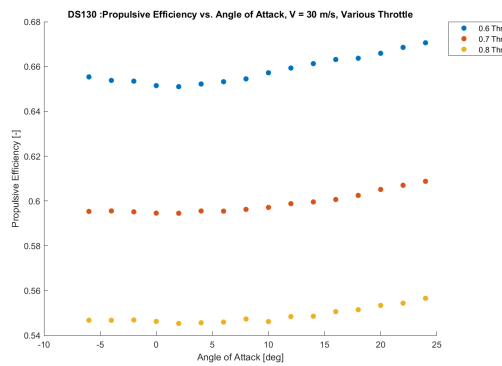


Figure B.145: Propulsive Efficiency vs. Angle of Attack, V = 30 ms, Various Throttle

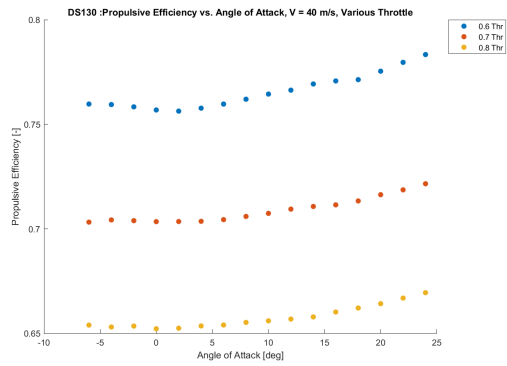


Figure B.146: Propulsive Efficiency vs. Angle of Attack,  $V = 40$  ms, Various Throttle

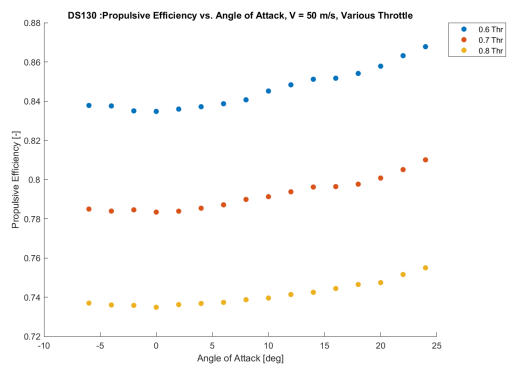


Figure B.147: Propulsive Efficiency vs. Angle of Attack,  $V = 50$  ms, Various Throttle

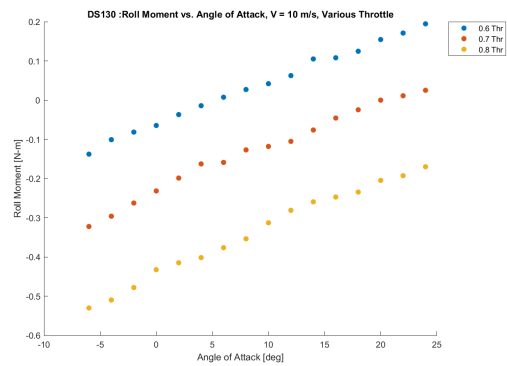


Figure B.148: Roll Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle

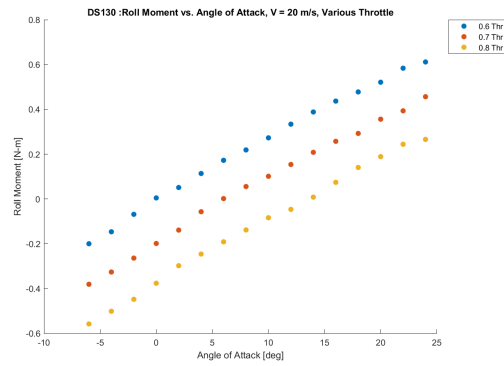


Figure B.149: Roll Moment vs. Angle of Attack, V = 20 ms, Various Throttle

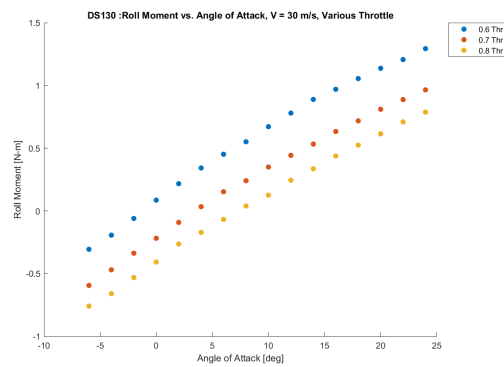


Figure B.150: Roll Moment vs. Angle of Attack, V = 30 ms, Various Throttle

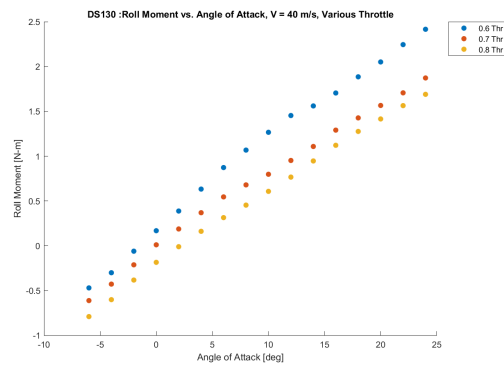


Figure B.151: Roll Moment vs. Angle of Attack, V = 40 ms, Various Throttle

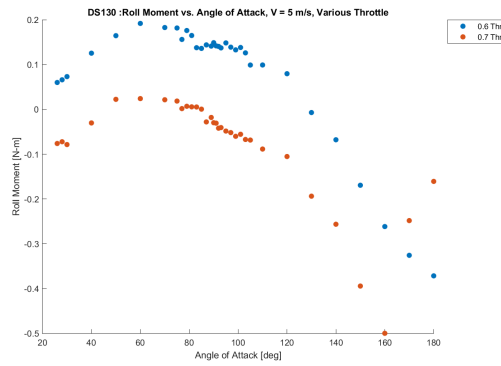


Figure B.152: Roll Moment vs. Angle of Attack,  $V = 5$  ms, Various Throttle,all

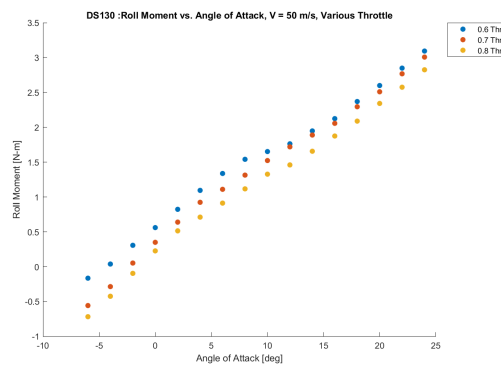


Figure B.153: Roll Moment vs. Angle of Attack,  $V = 50$  ms, Various Throttle

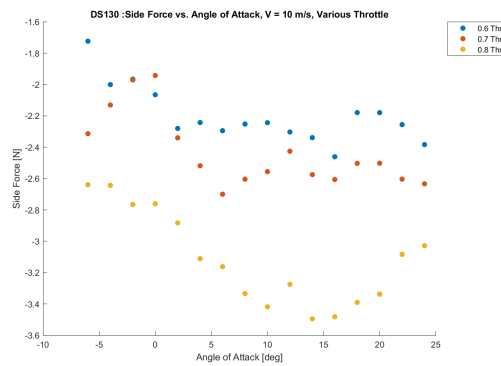


Figure B.154: Side Force vs. Angle of Attack,  $V = 10$  ms, Various Throttle

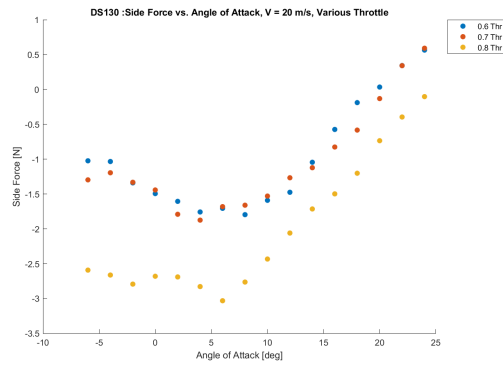


Figure B.155: Side Force vs. Angle of Attack,  $V = 20$  ms, Various Throttle

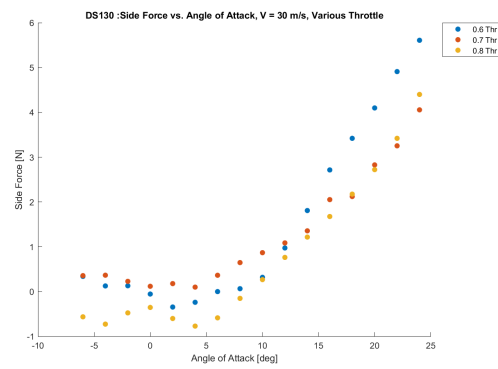


Figure B.156: Side Force vs. Angle of Attack,  $V = 30$  ms, Various Throttle

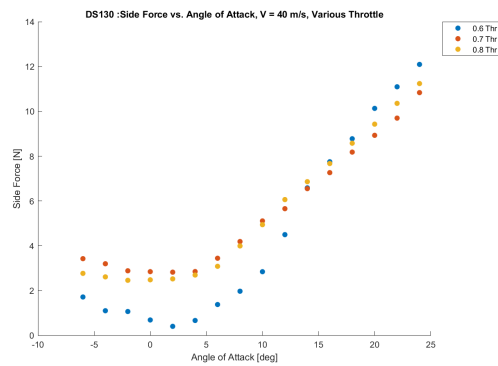


Figure B.157: Side Force vs. Angle of Attack,  $V = 40$  ms, Various Throttle

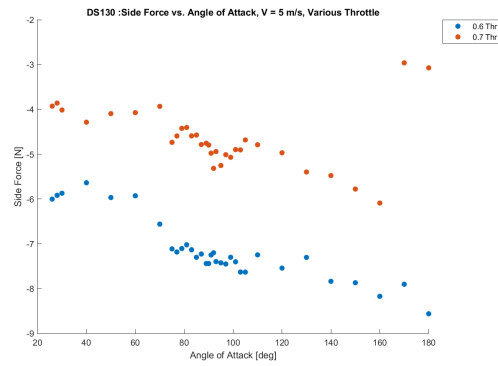


Figure B.158: Side Force vs. Angle of Attack, V = 5 ms, Various Throttle,all

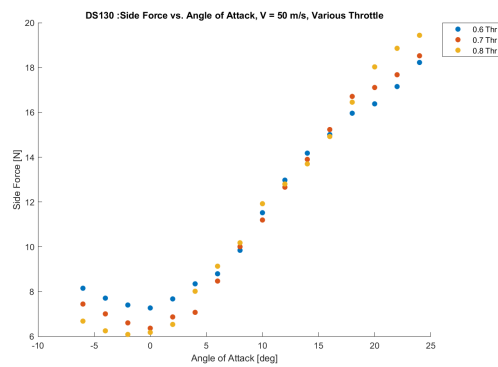


Figure B.159: Side Force vs. Angle of Attack, V = 50 ms, Various Throttle

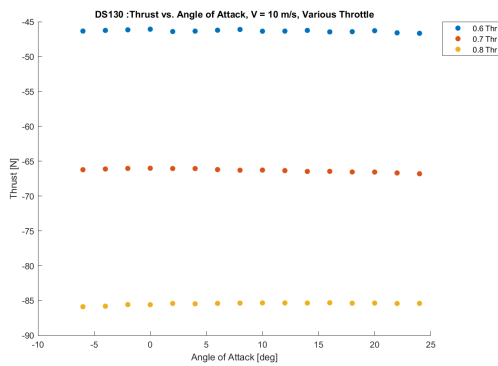


Figure B.160: Thrust vs. Angle of Attack, V = 10 ms, Various Throttle

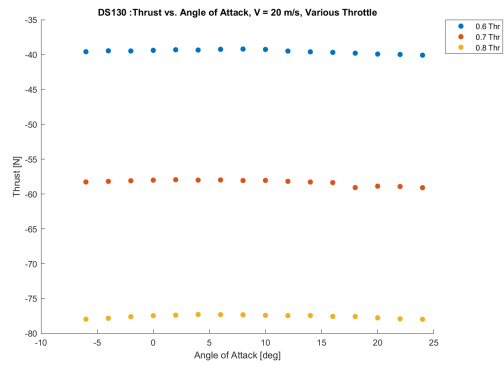


Figure B.161: Thrust vs. Angle of Attack,  $V = 20$  ms, Various Throttle

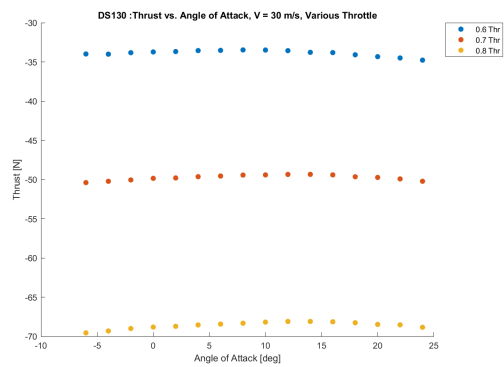


Figure B.162: Thrust vs. Angle of Attack,  $V = 30$  ms, Various Throttle

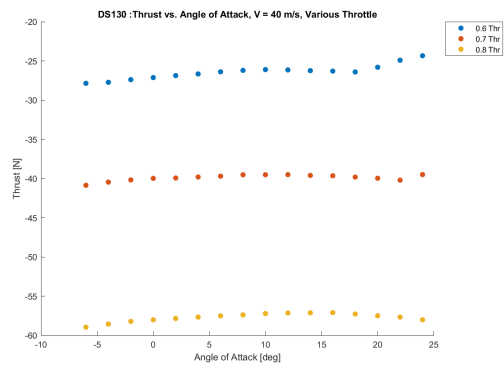


Figure B.163: Thrust vs. Angle of Attack,  $V = 40$  ms, Various Throttle

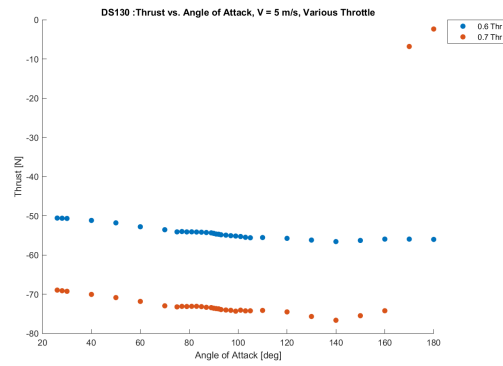


Figure B.164: Thrust vs. Angle of Attack,  $V = 5$  ms, Various Throttle,all

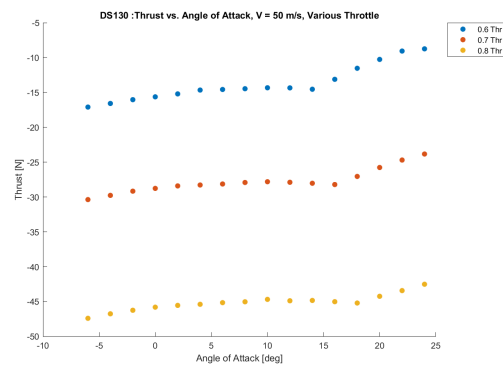


Figure B.165: Thrust vs. Angle of Attack,  $V = 50$  ms, Various Throttle

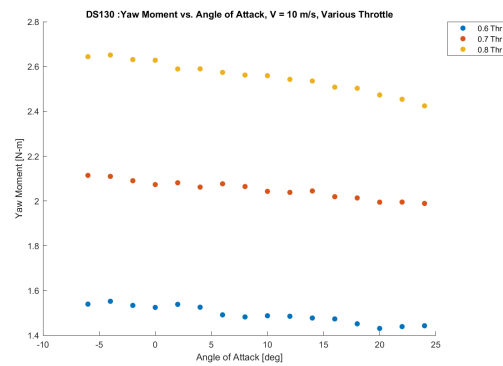


Figure B.166: Yaw Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle



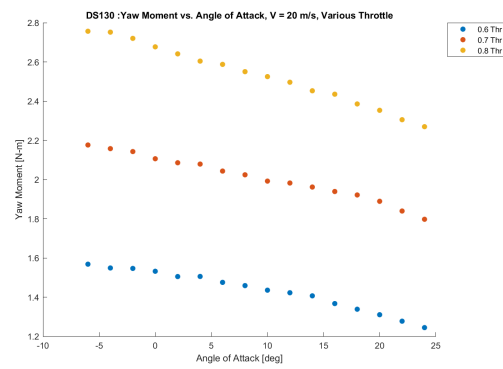


Figure B.167: Yaw Moment vs. Angle of Attack, V = 20 ms, Various Throttle

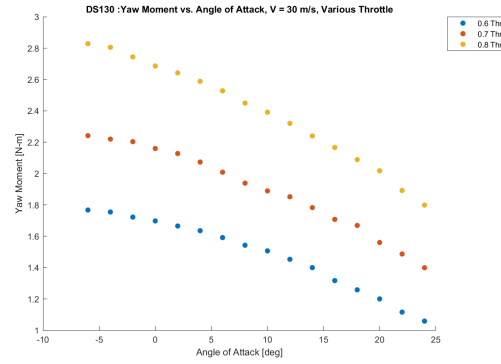


Figure B.168: Yaw Moment vs. Angle of Attack, V = 30 ms, Various Throttle

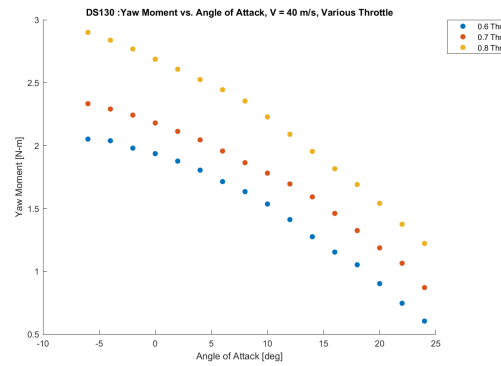


Figure B.169: Yaw Moment vs. Angle of Attack, V = 40 ms, Various Throttle

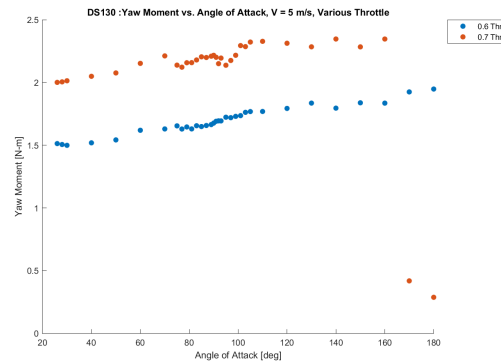


Figure B.170: Yaw Moment vs. Angle of Attack, V = 5 ms, Various Throttle,all

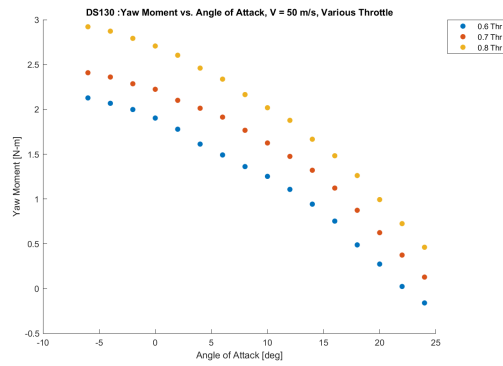


Figure B.171: Yaw Moment vs. Angle of Attack,  $V = 50$  ms, Various Throttle

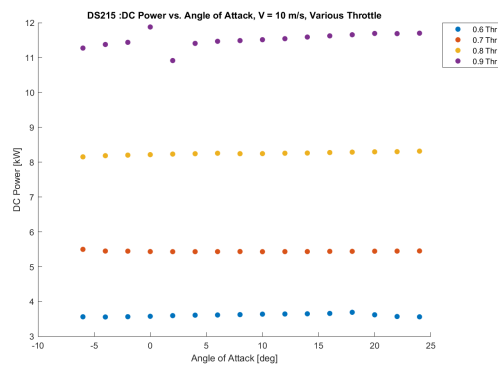


Figure B.172: DC Power vs. Angle of Attack,  $V = 10$  ms, Various Throttle

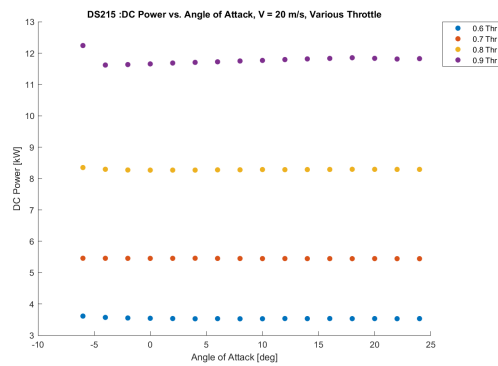


Figure B.173: DC Power vs. Angle of Attack,  $V = 20$  ms, Various Throttle

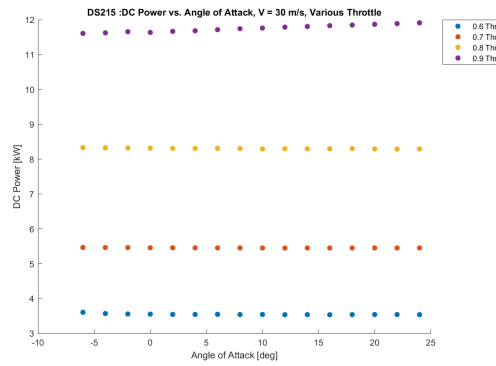


Figure B.174: DC Power vs. Angle of Attack, V = 30 ms, Various Throttle

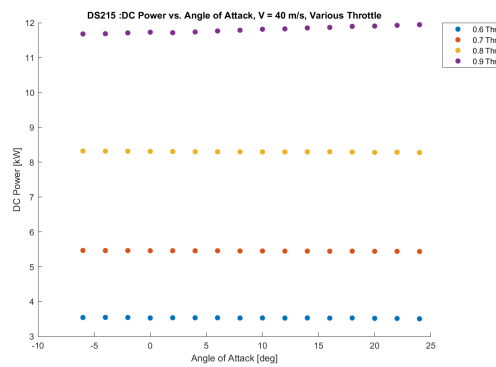


Figure B.175: DC Power vs. Angle of Attack, V = 40 ms, Various Throttle

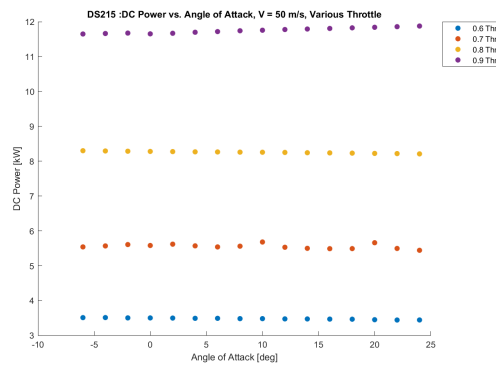


Figure B.176: DC Power vs. Angle of Attack, V = 50 ms, Various Throttle

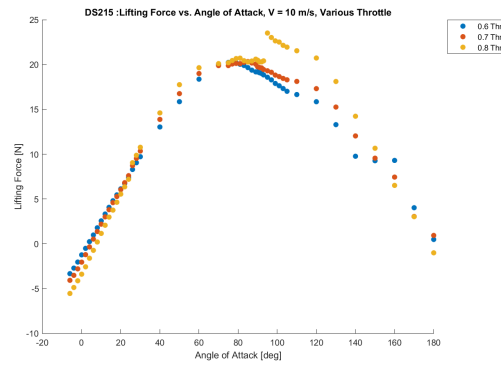


Figure B.177: Lifting Force vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all

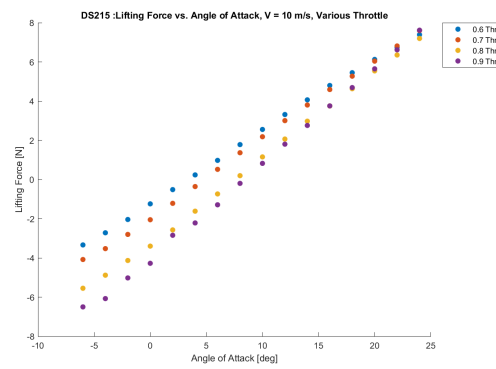


Figure B.178: Lifting Force vs. Angle of Attack,  $V = 10$  ms, Various Throttle

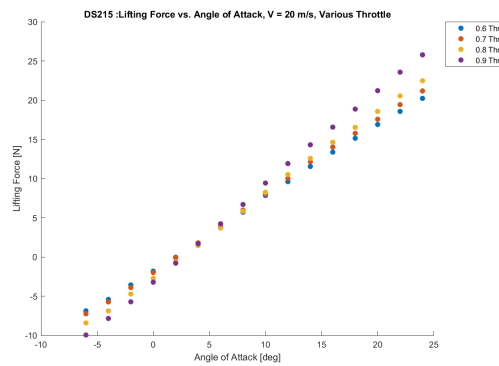


Figure B.179: Lifting Force vs. Angle of Attack,  $V = 20$  ms, Various Throttle

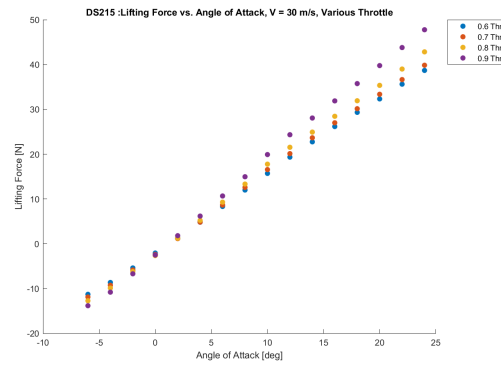


Figure B.180: Lifting Force vs. Angle of Attack, V = 30 ms, Various Throttle

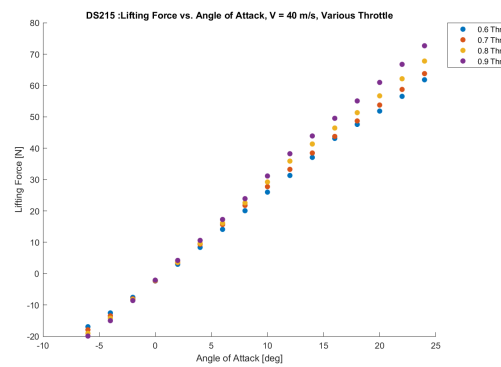


Figure B.181: Lifting Force vs. Angle of Attack, V = 40 ms, Various Throttle

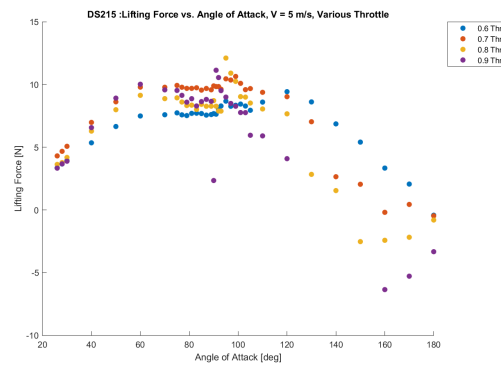


Figure B.182: Lifting Force vs. Angle of Attack, V = 5 ms, Various Throttle,all

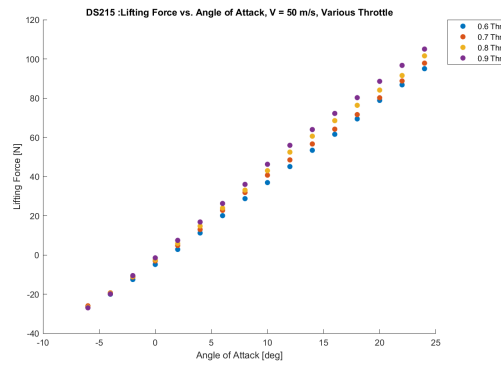


Figure B.183: Lifting Force vs. Angle of Attack,  $V = 50$  ms, Various Throttle

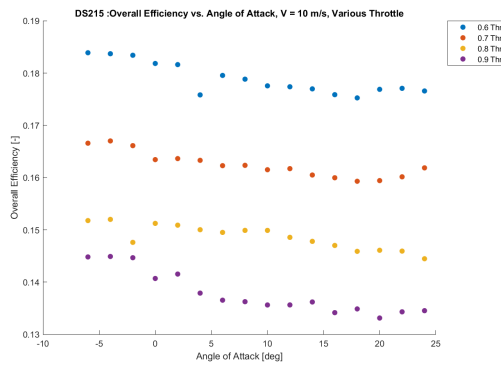


Figure B.184: Overall Efficiency vs. Angle of Attack,  $V = 10$  ms, Various Throttle

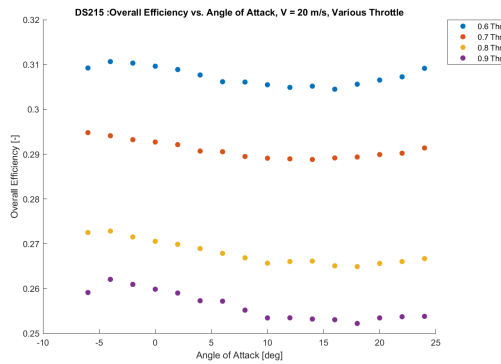


Figure B.185: Overall Efficiency vs. Angle of Attack,  $V = 20$  ms, Various Throttle

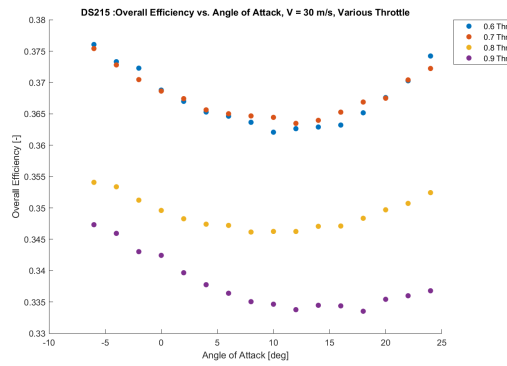


Figure B.186: Overall Efficiency vs. Angle of Attack,  $V = 30$  ms, Various Throttle

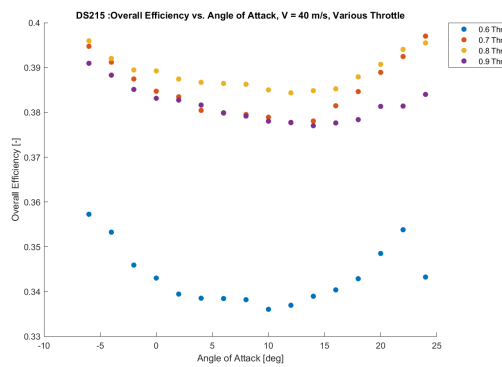


Figure B.187: Overall Efficiency vs. Angle of Attack,  $V = 40$  ms, Various Throttle

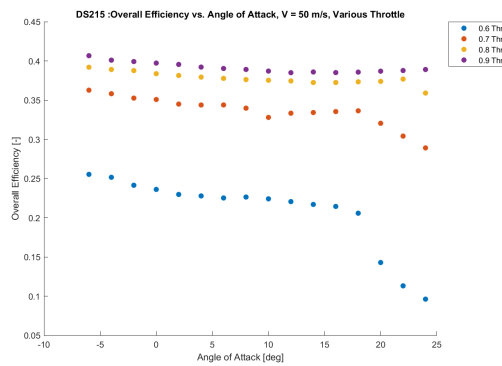


Figure B.188: Overall Efficiency vs. Angle of Attack,  $V = 50$  ms, Various Throttle



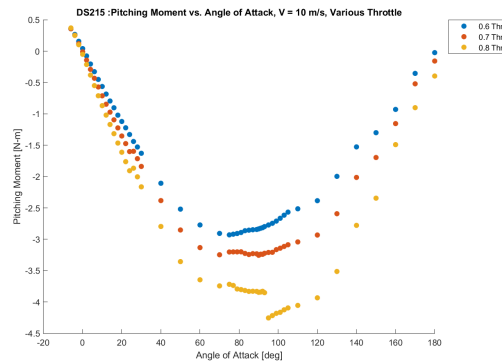


Figure B.189: Pitching Moment vs. Angle of Attack, V = 10 ms, Various Throttle,all

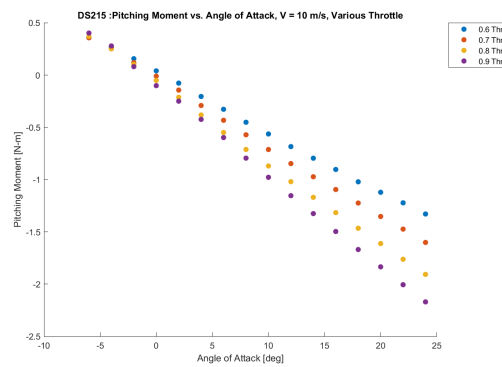


Figure B.190: Pitching Moment vs. Angle of Attack, V = 10 ms, Various Throttle

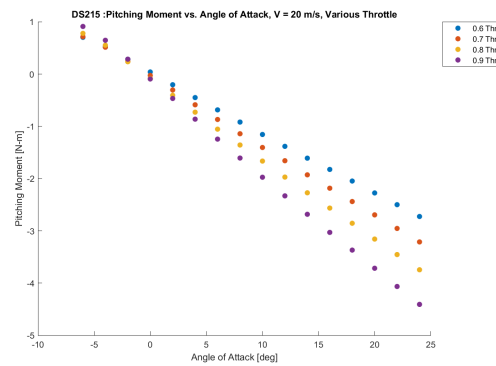


Figure B.191: Pitching Moment vs. Angle of Attack, V = 20 ms, Various Throttle

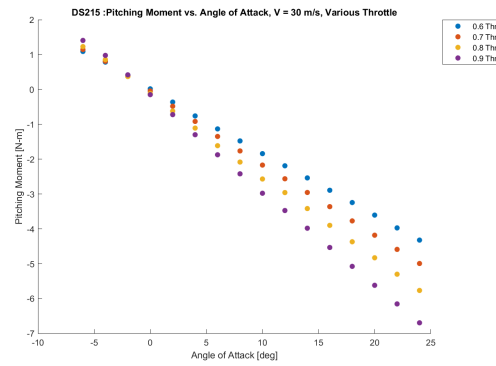


Figure B.192: Pitching Moment vs. Angle of Attack, V = 30 ms, Various Throttle

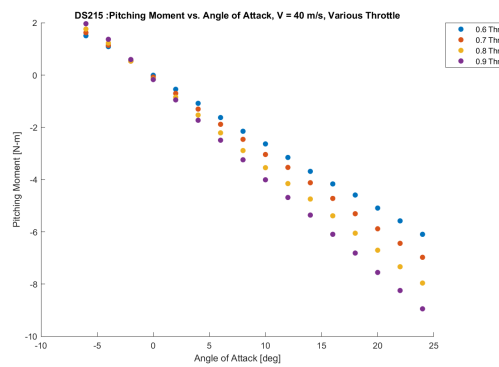


Figure B.193: Pitching Moment vs. Angle of Attack, V = 40 ms, Various Throttle

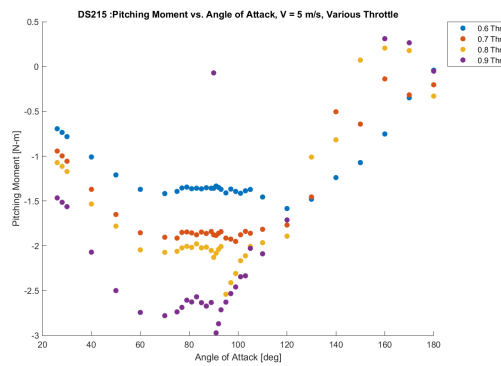


Figure B.194: Pitching Moment vs. Angle of Attack, V = 5 ms, Various Throttle,all

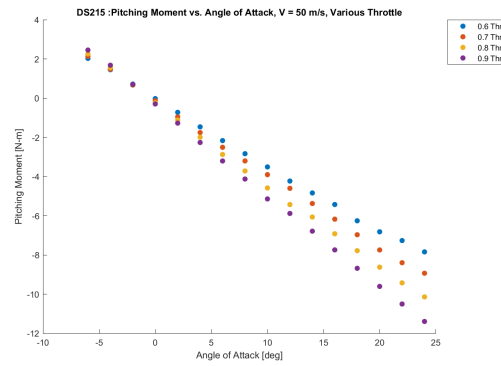


Figure B.195: Pitching Moment vs. Angle of Attack,  $V = 50$  ms, Various Throttle

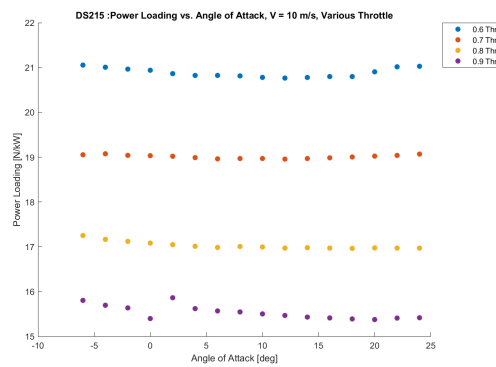


Figure B.196: Power Loading vs. Angle of Attack,  $V = 10$  ms, Various Throttle

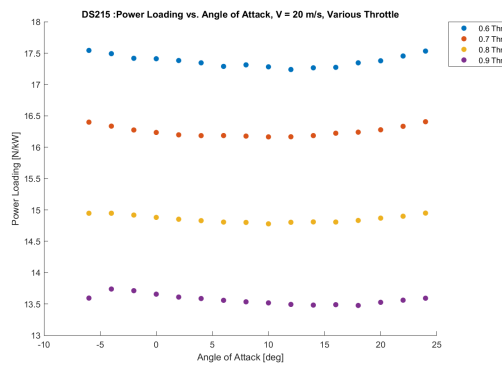


Figure B.197: Power Loading vs. Angle of Attack,  $V = 20$  ms, Various Throttle

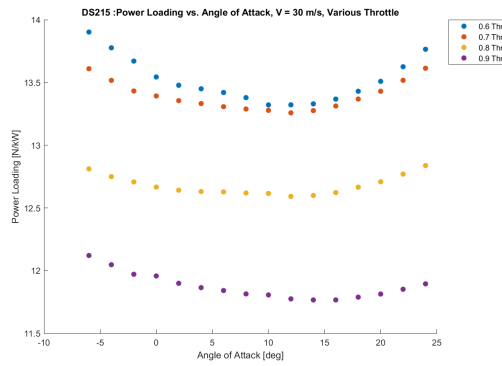


Figure B.198: Power Loading vs. Angle of Attack,  $V = 30$  ms, Various Throttle

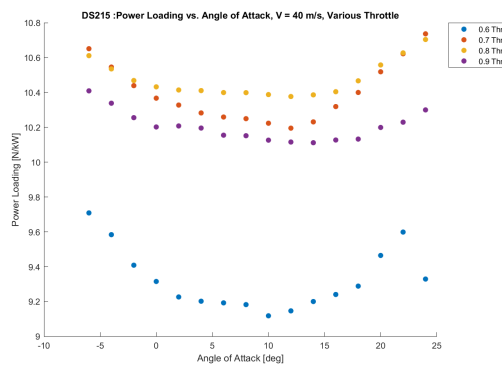


Figure B.199: Power Loading vs. Angle of Attack,  $V = 40$  ms, Various Throttle

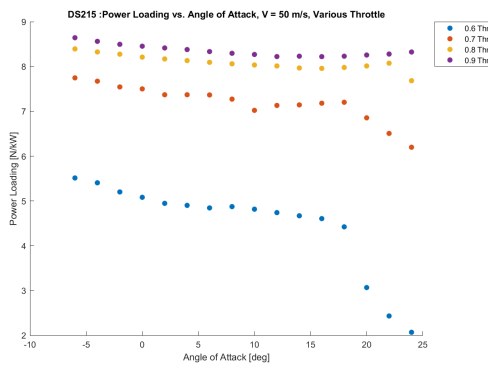


Figure B.200: Power Loading vs. Angle of Attack,  $V = 50$  ms, Various Throttle

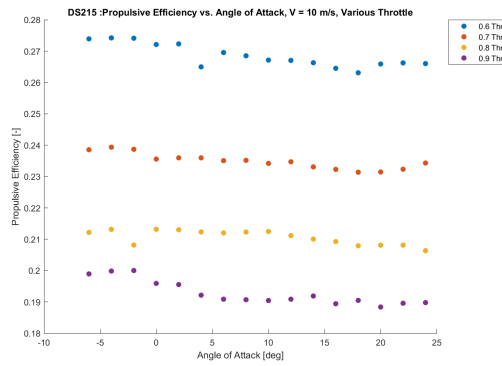


Figure B.201: Propulsive Efficiency vs. Angle of Attack,  $V = 10$  ms, Various Throttle

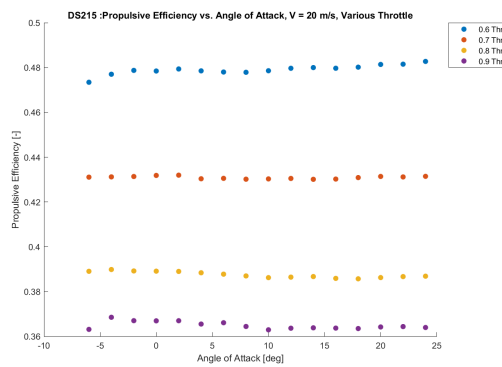


Figure B.202: Propulsive Efficiency vs. Angle of Attack,  $V = 20$  ms, Various Throttle

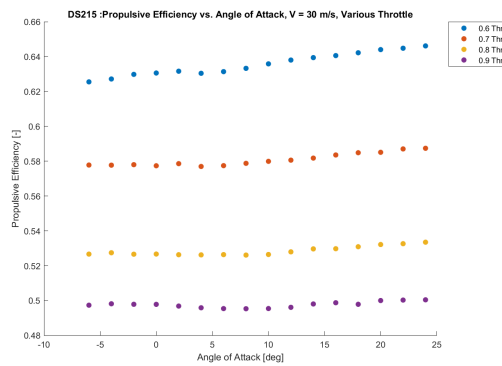


Figure B.203: Propulsive Efficiency vs. Angle of Attack,  $V = 30$  ms, Various Throttle

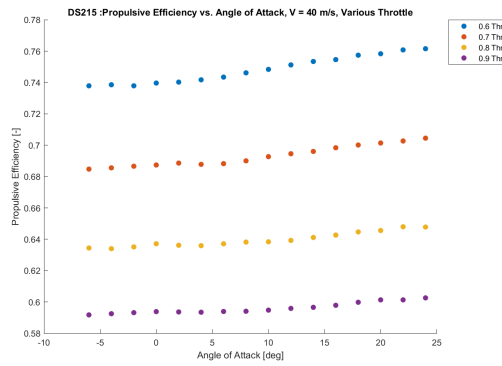


Figure B.204: Propulsive Efficiency vs. Angle of Attack,  $V = 40$  ms, Various Throttle

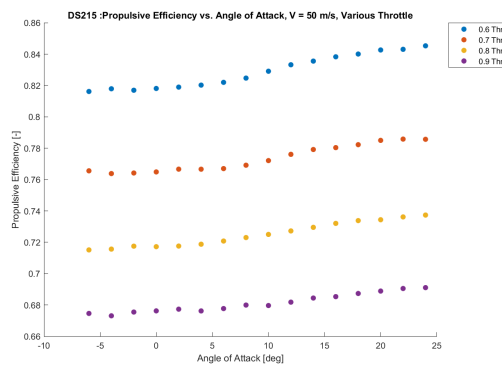


Figure B.205: Propulsive Efficiency vs. Angle of Attack,  $V = 50$  ms, Various Throttle

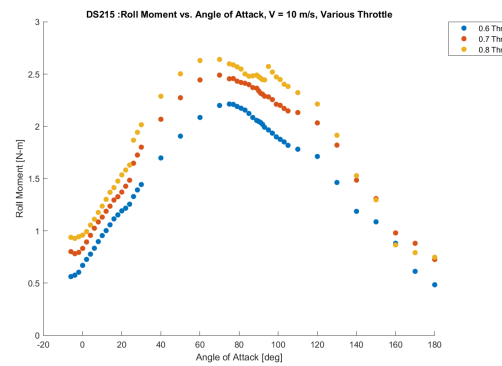


Figure B.206: Roll Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all

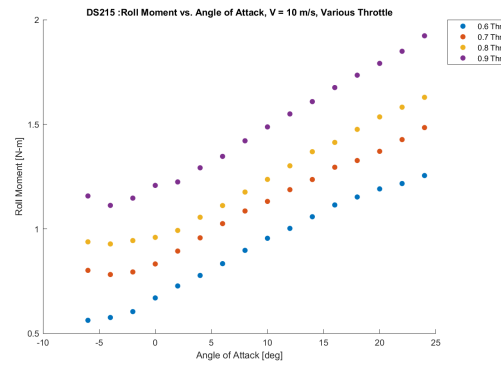


Figure B.207: Roll Moment vs. Angle of Attack, V = 10 ms, Various Throttle

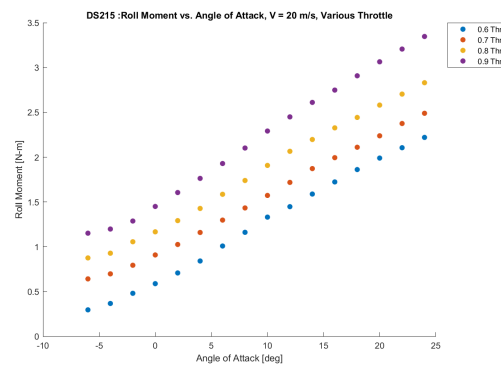


Figure B.208: Roll Moment vs. Angle of Attack, V = 20 ms, Various Throttle

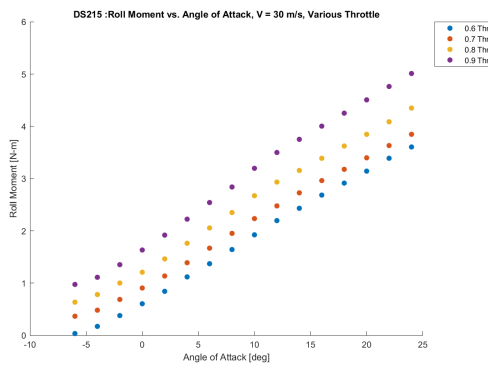


Figure B.209: Roll Moment vs. Angle of Attack, V = 30 ms, Various Throttle

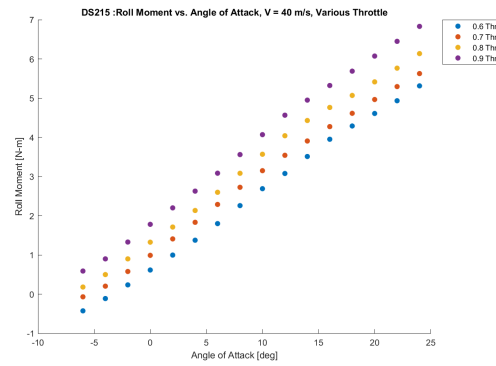


Figure B.210: Roll Moment vs. Angle of Attack, V = 40 ms, Various Throttle

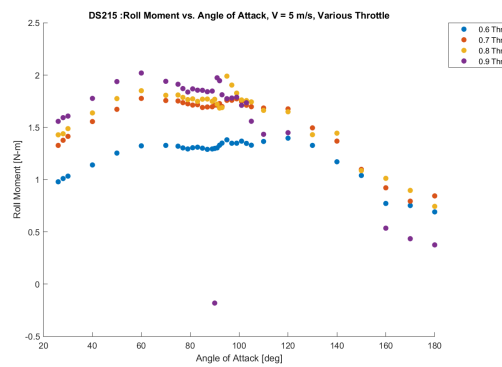


Figure B.211: Roll Moment vs. Angle of Attack, V = 5 ms, Various Throttle,all

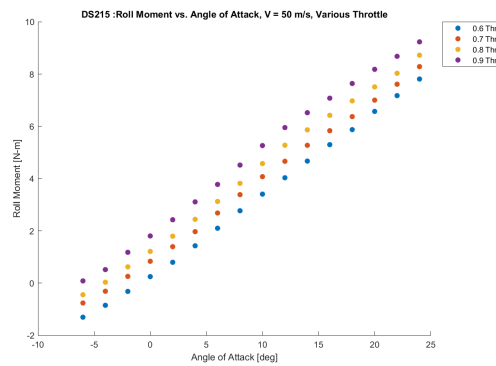


Figure B.212: Roll Moment vs. Angle of Attack, V = 50 ms, Various Throttle



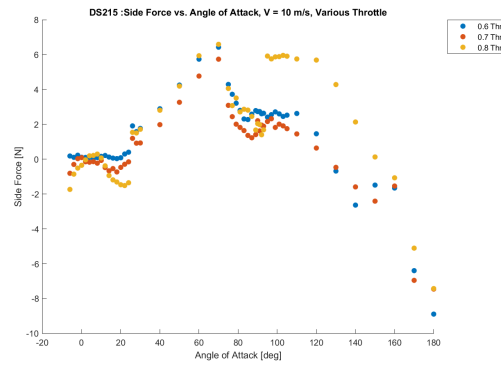


Figure B.213: Side Force vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all

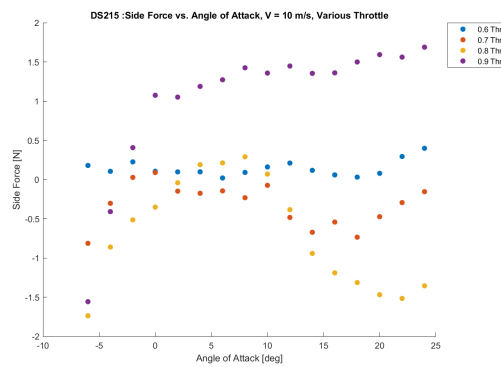


Figure B.214: Side Force vs. Angle of Attack,  $V = 10$  ms, Various Throttle

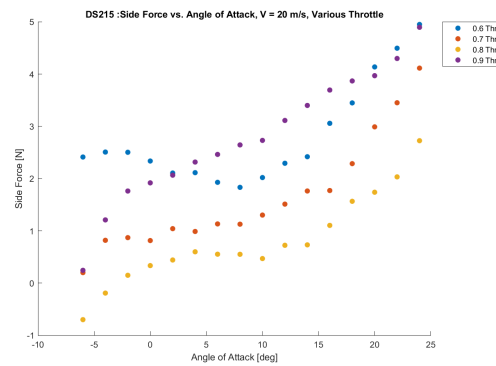


Figure B.215: Side Force vs. Angle of Attack,  $V = 20$  ms, Various Throttle

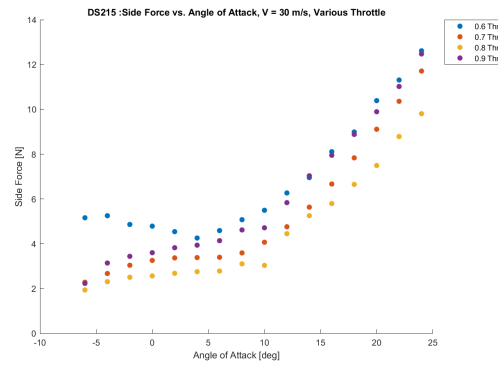


Figure B.216: Side Force vs. Angle of Attack, V = 30 ms, Various Throttle

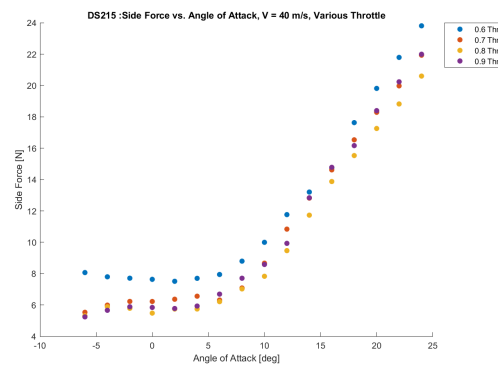


Figure B.217: Side Force vs. Angle of Attack, V = 40 ms, Various Throttle

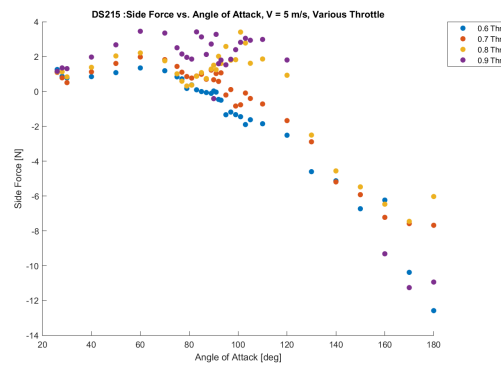


Figure B.218: Side Force vs. Angle of Attack, V = 5 ms, Various Throttle,all

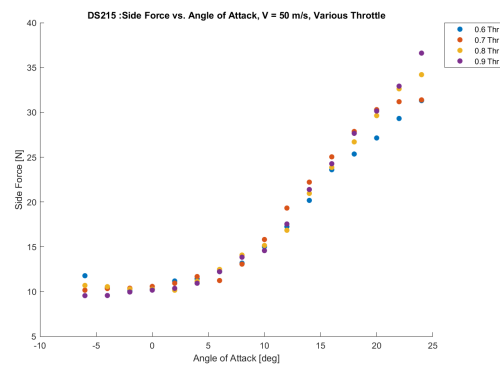


Figure B.219: Side Force vs. Angle of Attack, V = 50 ms, Various Throttle

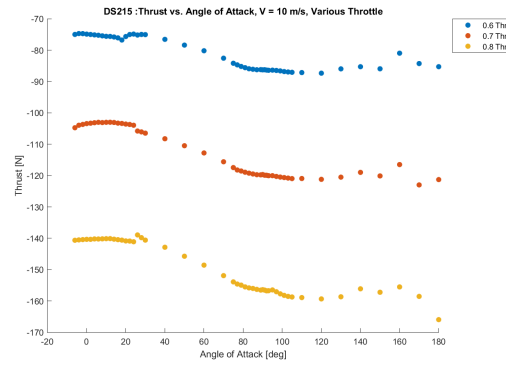


Figure B.220: Thrust vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all

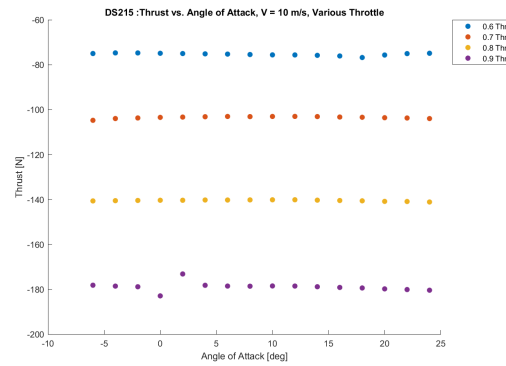


Figure B.221: Thrust vs. Angle of Attack,  $V = 10$  ms, Various Throttle

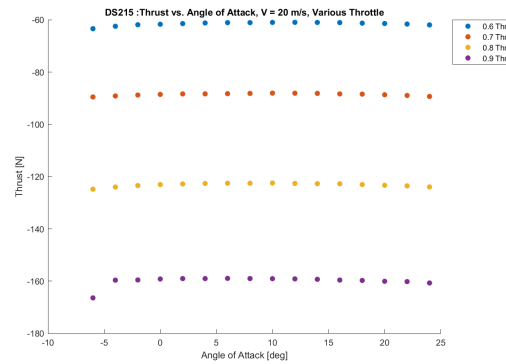


Figure B.222: Thrust vs. Angle of Attack,  $V = 20$  ms, Various Throttle

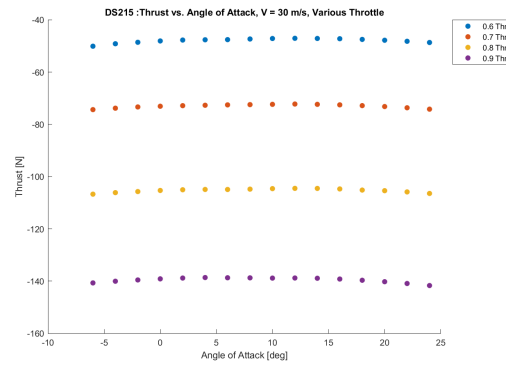


Figure B.223: Thrust vs. Angle of Attack, V = 30 ms, Various Throttle

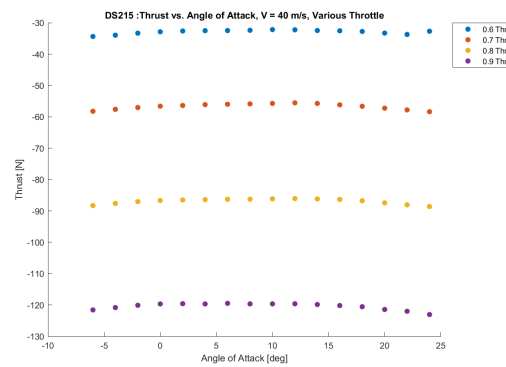


Figure B.224: Thrust vs. Angle of Attack, V = 40 ms, Various Throttle

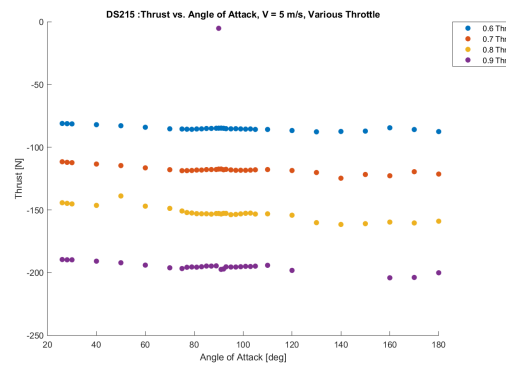


Figure B.225: Thrust vs. Angle of Attack, V = 5 ms, Various Throttle,all

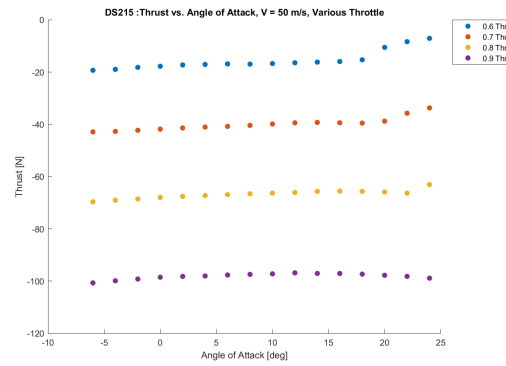


Figure B.226: Thrust vs. Angle of Attack,  $V = 50$  ms, Various Throttle

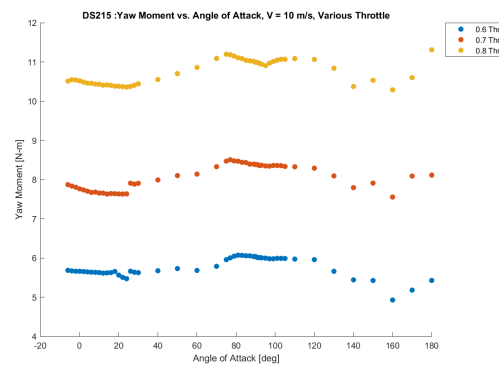


Figure B.227: Yaw Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle,all

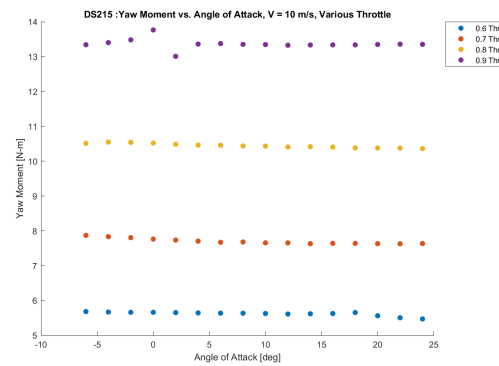


Figure B.228: Yaw Moment vs. Angle of Attack,  $V = 10$  ms, Various Throttle

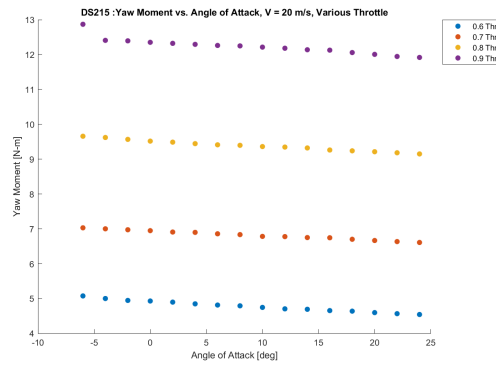


Figure B.229: Yaw Moment vs. Angle of Attack, V = 20 ms, Various Throttle

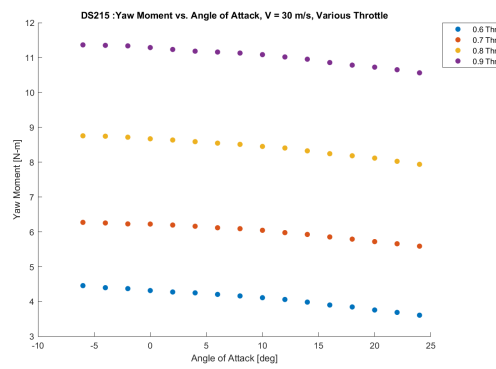


Figure B.230: Yaw Moment vs. Angle of Attack, V = 30 ms, Various Throttle

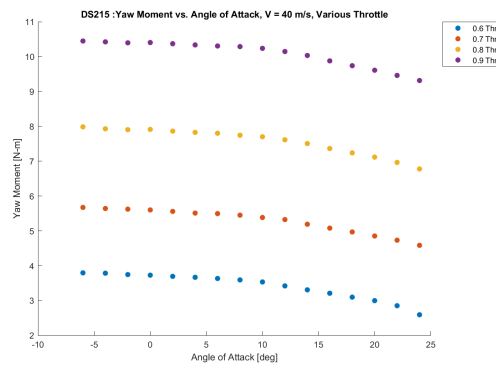


Figure B.231: Yaw Moment vs. Angle of Attack, V = 40 ms, Various Throttle

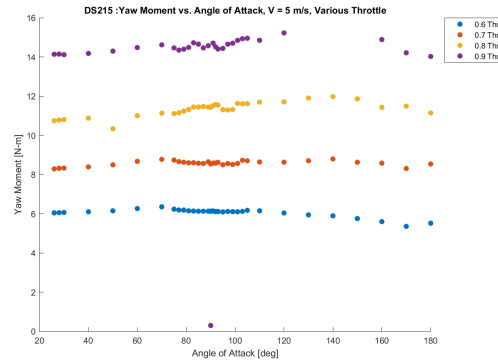


Figure B.232: Yaw Moment vs. Angle of Attack,  $V = 5 \text{ ms}$ , Various Throttle,all

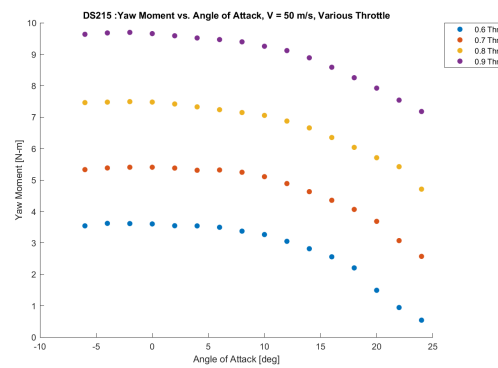


Figure B.233: Yaw Moment vs. Angle of Attack,  $V = 50 \text{ ms}$ , Various Throttle



# APPENDIX C

## COMPREHENSIVE DATA FROM HIGH SPEED EDF INTEGRATION TEST

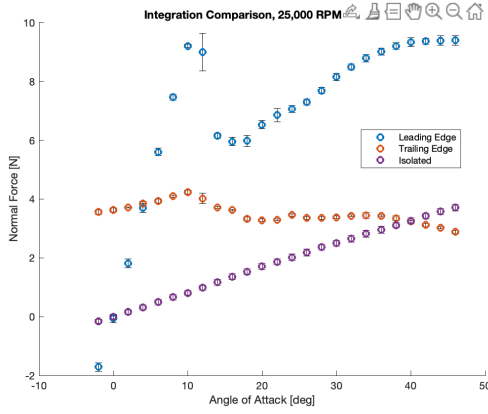


Figure C.1: Integration Comparison, 25,000 RPM, 10 ms1Comp<sub>Lift</sub>

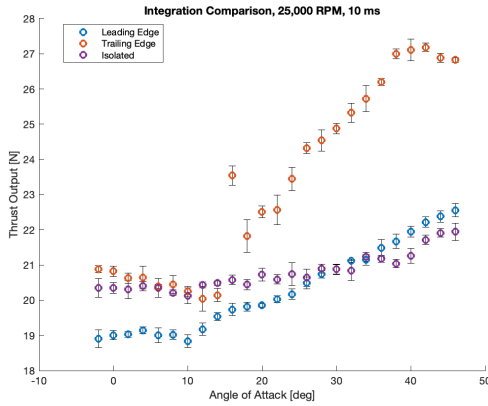


Figure C.2: Integration Comparison, 25,000 RPM, 10 ms3Comp

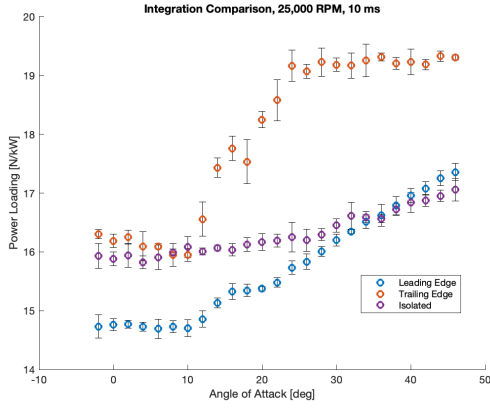


Figure C.3: Integration Comparison, 25,000 RPM, 10 ms  $3Comp_P L$

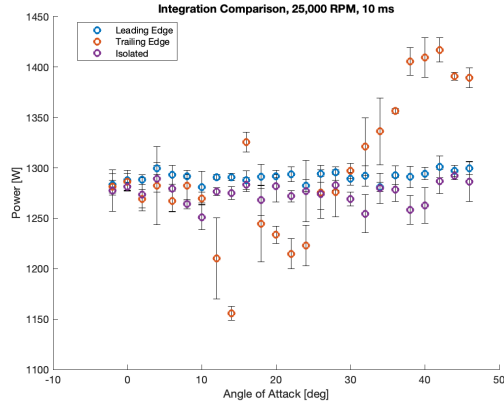


Figure C.4: Integration Comparison, 25,000 RPM, 10 ms  $7Comp_{Lift}$

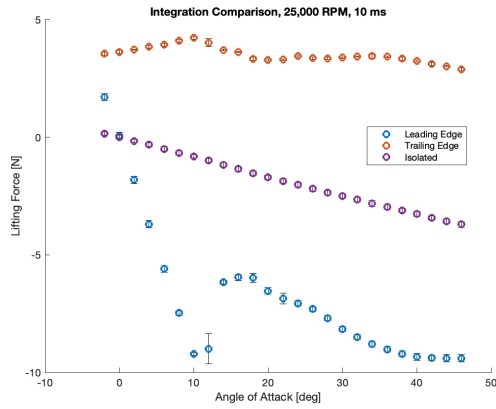


Figure C.5: Integration Comparison, 25,000 RPM, 10 ms  $Comp$

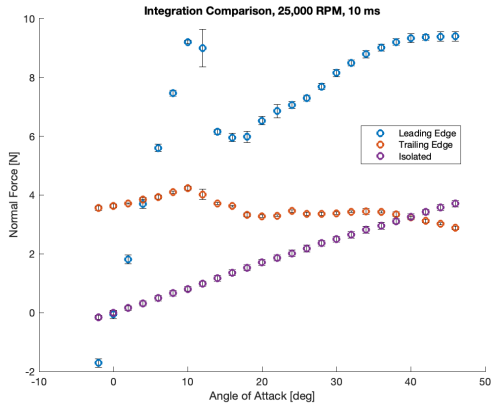


Figure C.6: Integration Comparison, 25,000 RPM, 10 ms  $Comp_{Lift}$

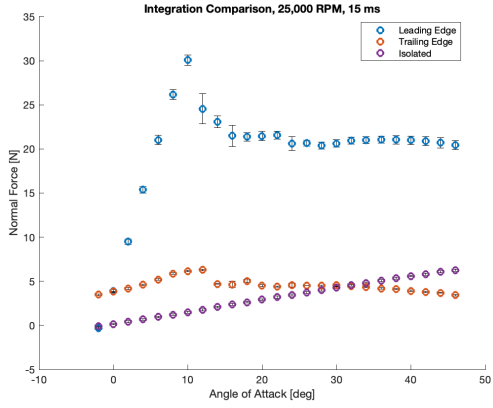


Figure C.7: Integration Comparison, 25,000 RPM, 15 ms  $Comp_{Lift}$

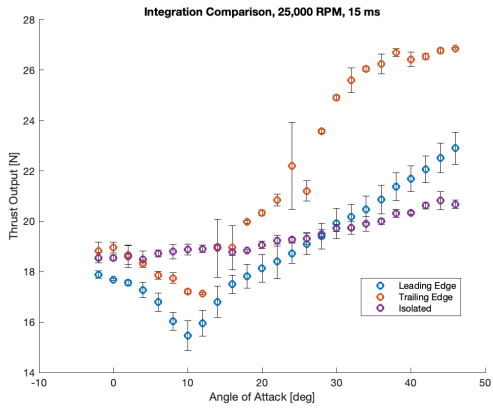


Figure C.8: Integration Comparison, 25,000 RPM, 15 ms  $Comp_{Thrust}$

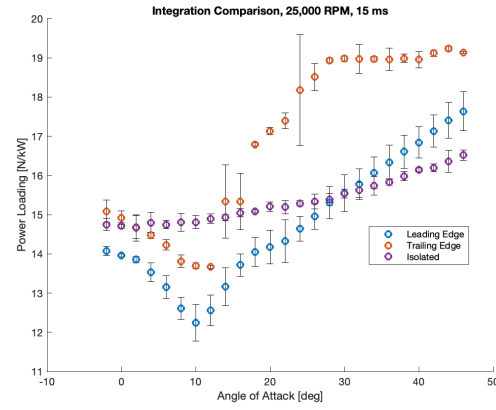


Figure C.9: Integration Comparison, 25,000 RPM, 15 ms  $3Comp_P L$

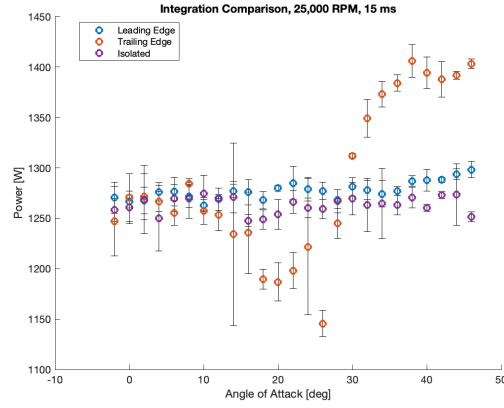


Figure C.10: Integration Comparison, 25,000 RPM, 15 ms  $7Comp_{Lift}$

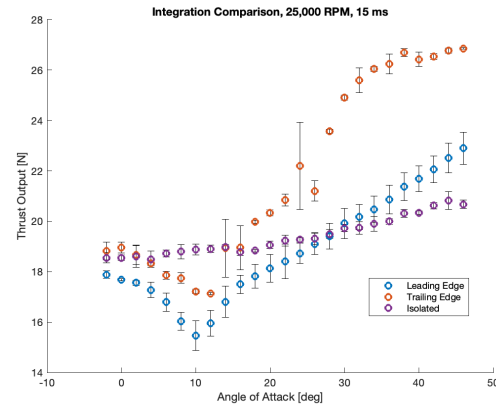


Figure C.11: Integration Comparison, 25,000 RPM, 15 ms  $Comp$

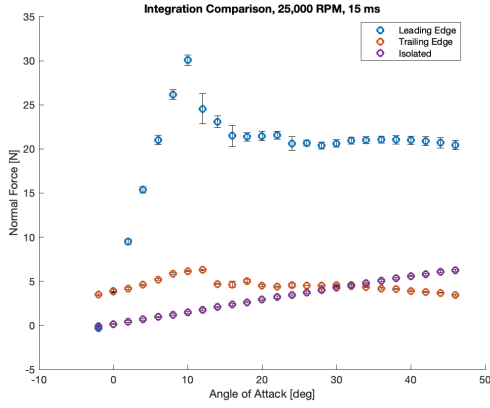


Figure C.12: Integration Comparison, 25,000 RPM, 15 ms  $Comp_{Lift}$

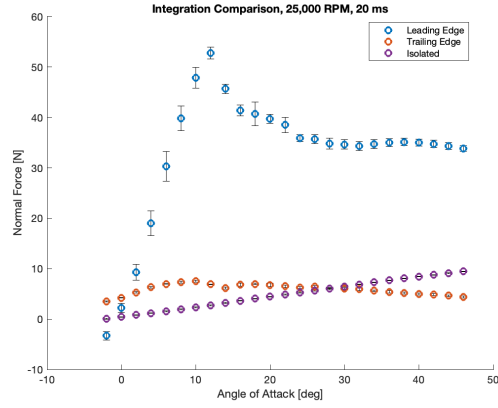


Figure C.13: Integration Comparison, 25,000 RPM, 20 ms  $1Comp_{Lift}$

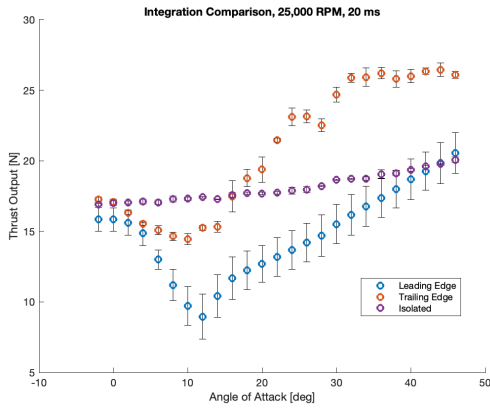


Figure C.14: Integration Comparison, 25,000 RPM, 20 ms  $3Comp$

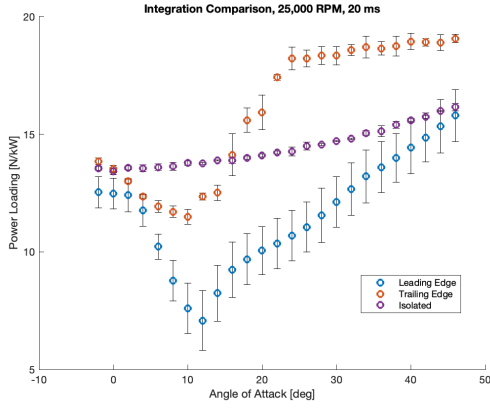


Figure C.15: Integration Comparison, 25,000 RPM, 20 ms  $3Comp_P L$

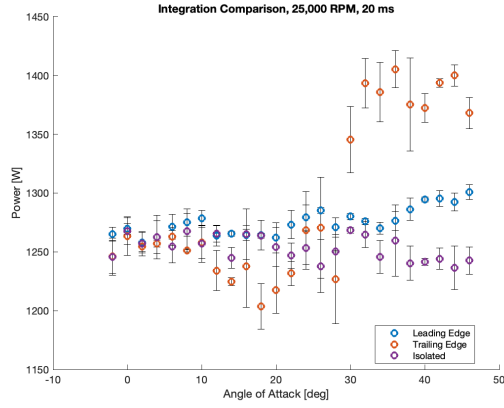


Figure C.16: Integration Comparison, 25,000 RPM, 20 ms  $7Comp_{Lift}$

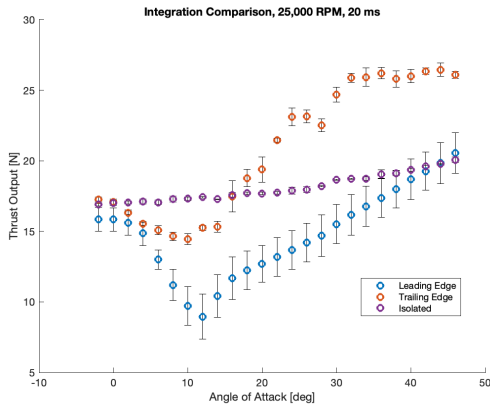


Figure C.17: Integration Comparison, 25,000 RPM, 20 ms  $Comp$

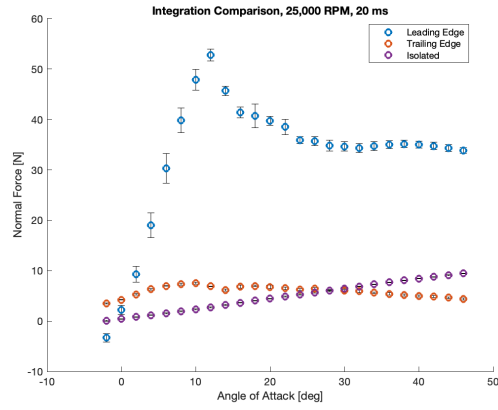


Figure C.18: Integration Comparison, 25,000 RPM, 20 ms  $Comp_{Lift}$

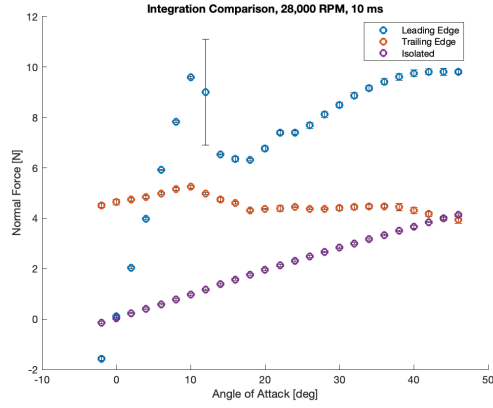


Figure C.19: Integration Comparison, 28,000 RPM, 10 ms  $1Comp_{Lift}$

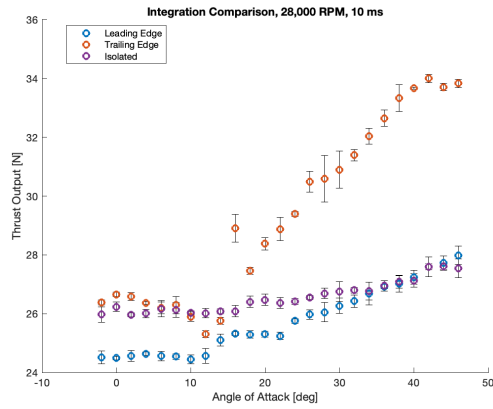


Figure C.20: Integration Comparison, 28,000 RPM, 10 ms  $3Comp$

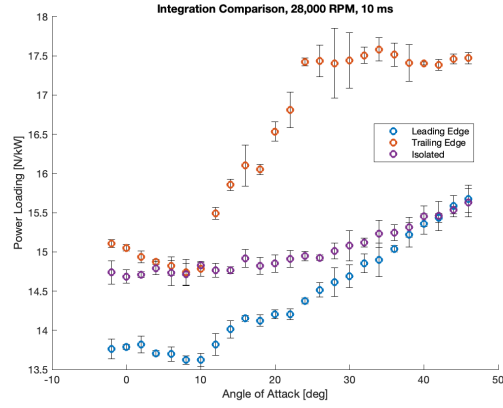


Figure C.21: Integration Comparison, 28,000 RPM, 10 ms  $3Comp_P L$

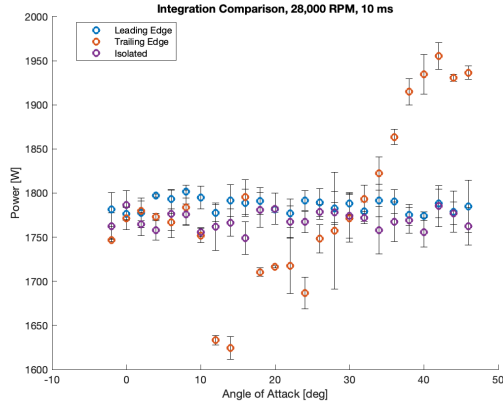


Figure C.22: Integration Comparison, 28,000 RPM, 10 ms  $7Comp_{Lift}$

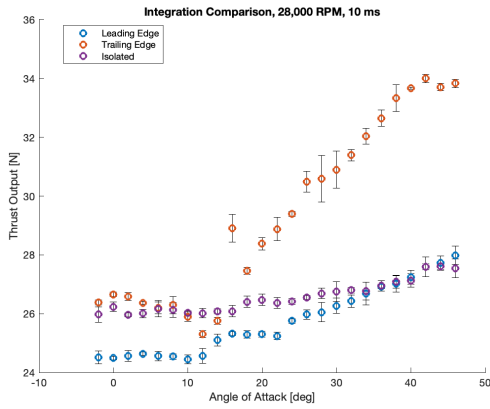


Figure C.23: Integration Comparison, 28,000 RPM, 10 ms  $Comp$



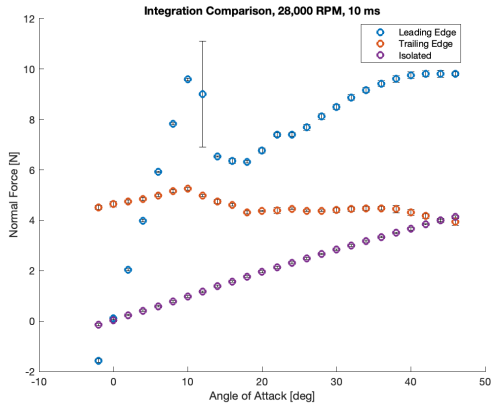


Figure C.24: Integration Comparison, 28,000 RPM, 10 ms  $Comp_{Lift}$

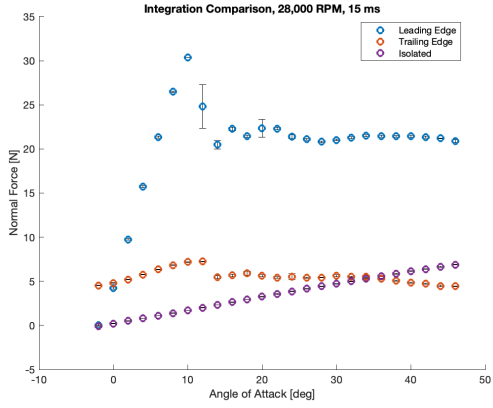


Figure C.25: Integration Comparison, 28,000 RPM, 15 ms  $Comp_{Lift}$

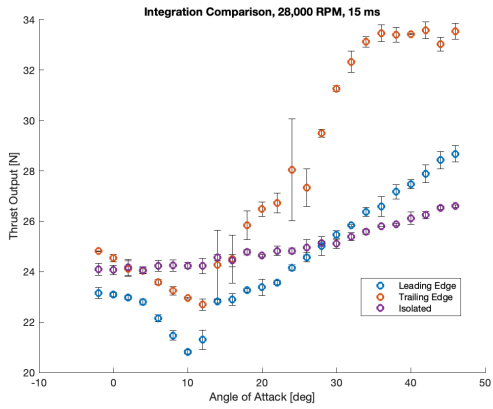


Figure C.26: Integration Comparison, 28,000 RPM, 15 ms  $Comp_{3}$

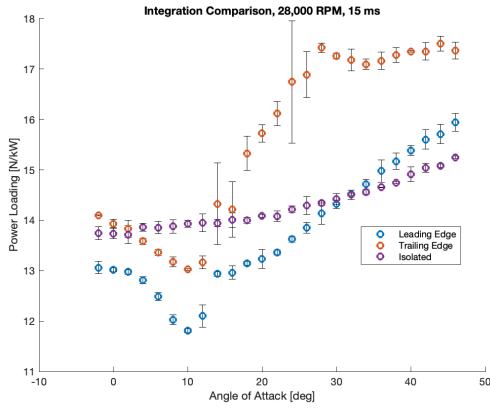


Figure C.27: Integration Comparison, 28,000 RPM, 15 ms  $3Comp_P L$

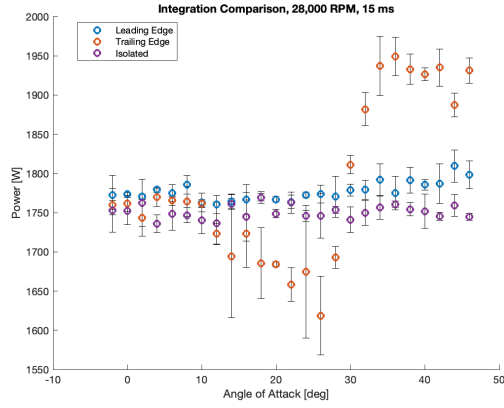


Figure C.28: Integration Comparison, 28,000 RPM, 15 ms  $7Comp_{Lift}$

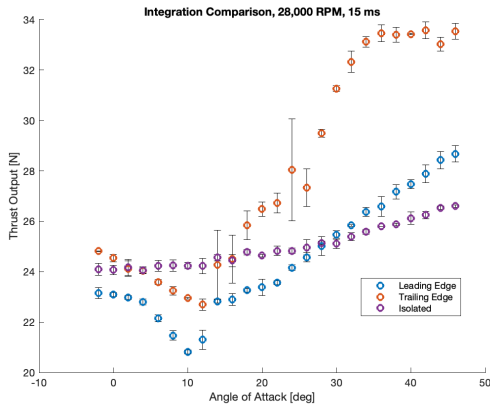


Figure C.29: Integration Comparison, 28,000 RPM, 15 ms  $Comp$

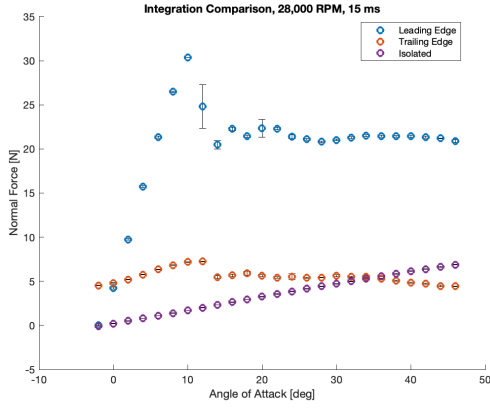


Figure C.30: Integration Comparison, 28,000 RPM, 15 ms  $Comp_{Lift}$

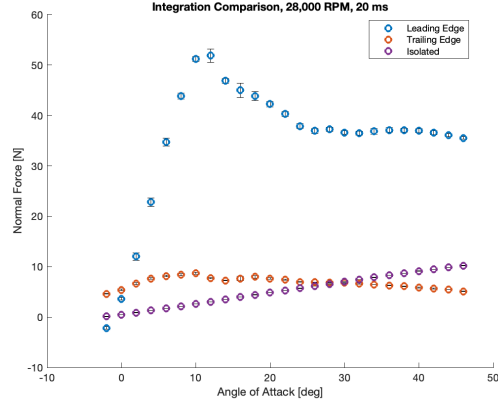


Figure C.31: Integration Comparison, 28,000 RPM, 20 ms  $Comp_{Lift}$

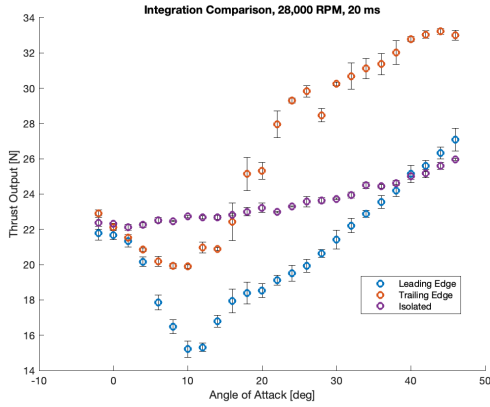


Figure C.32: Integration Comparison, 28,000 RPM, 20 ms  $Comp_{Thrust}$

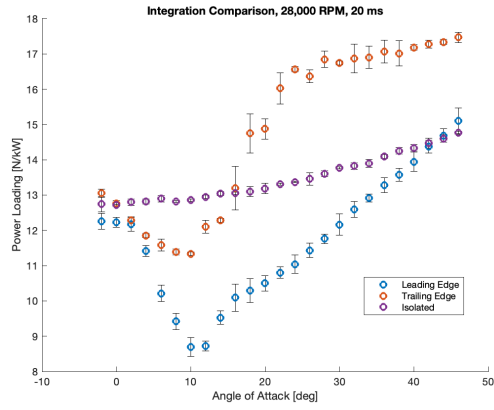


Figure C.33: Integration Comparison, 28,000 RPM, 20 ms  $3Comp_P L$

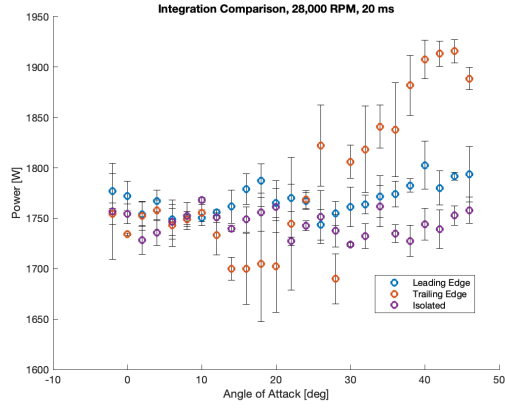


Figure C.34: Integration Comparison, 28,000 RPM, 20 ms  $7Comp_{Lift}$

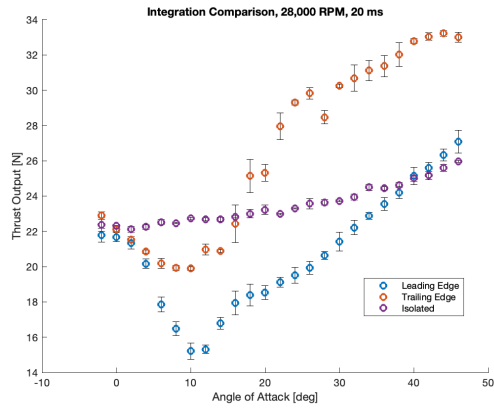


Figure C.35: Integration Comparison, 28,000 RPM, 20 ms  $Comp$

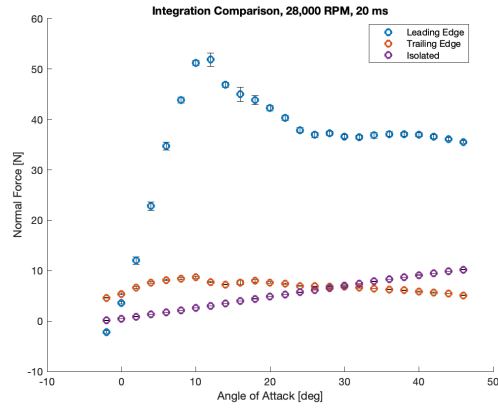


Figure C.36: Integration Comparison, 28,000 RPM, 20 ms  $Comp_{Lift}$

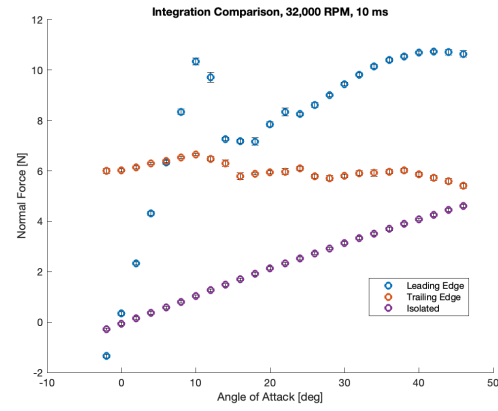


Figure C.37: Integration Comparison, 32,000 RPM, 10 ms  $1Comp_{Lift}$

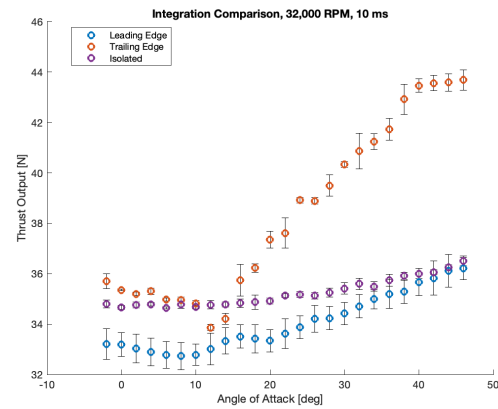


Figure C.38: Integration Comparison, 32,000 RPM, 10 ms  $3Comp$

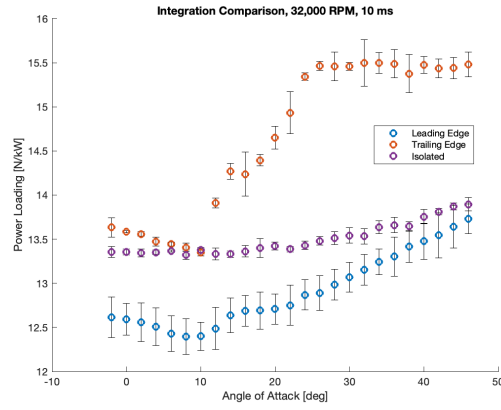


Figure C.39: Integration Comparison, 32,000 RPM, 10 ms  $3Comp_P L$

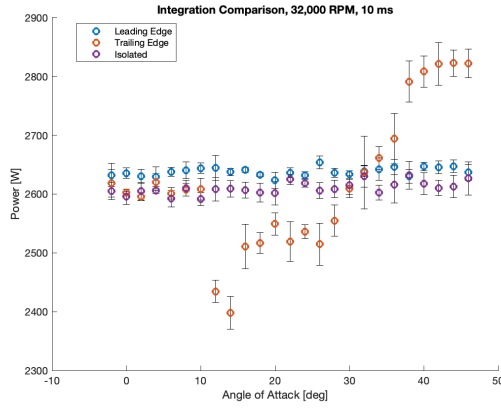


Figure C.40: Integration Comparison, 32,000 RPM, 10 ms  $7Comp_{Lift}$

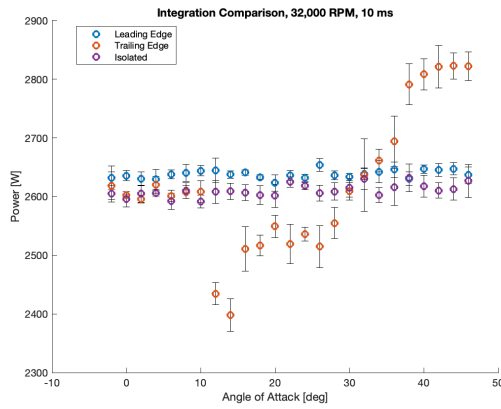


Figure C.41: Integration Comparison, 32,000 RPM, 10 ms  $7Comp_{Pow}$

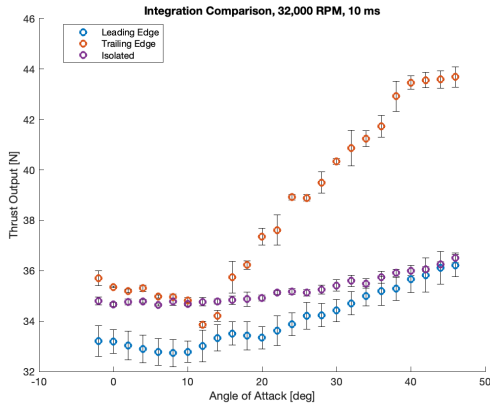


Figure C.42: Integration Comparison, 32,000 RPM, 10 msComp

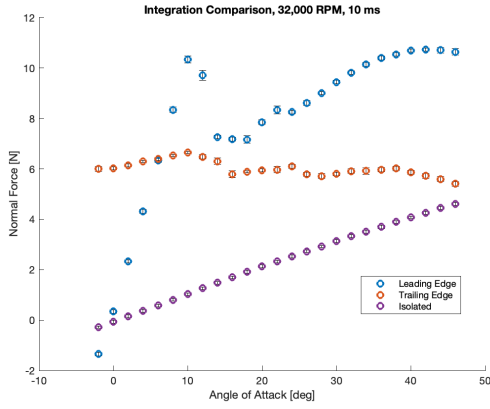


Figure C.43: Integration Comparison, 32,000 RPM, 10 msComp<sub>Lift</sub>

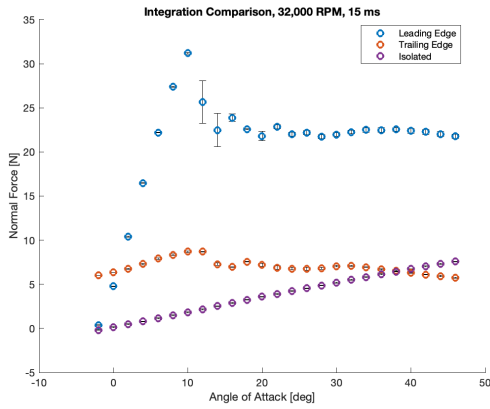


Figure C.44: Integration Comparison, 32,000 RPM, 15 ms1Comp<sub>Lift</sub>

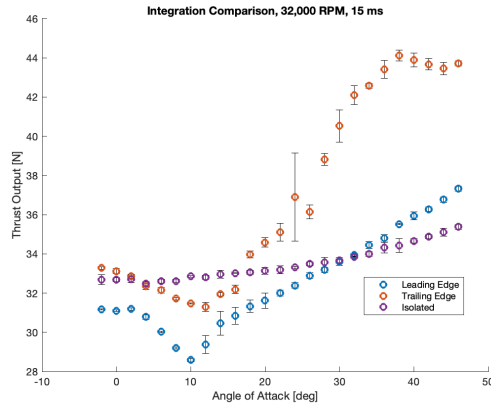


Figure C.45: Integration Comparison, 32,000 RPM, 15 ms3Comp

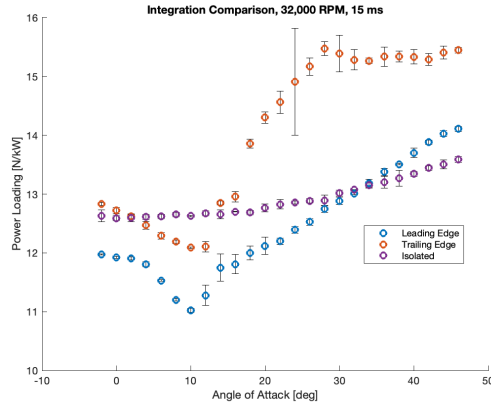


Figure C.46: Integration Comparison, 32,000 RPM, 15 ms3Comp<sub>PL</sub>

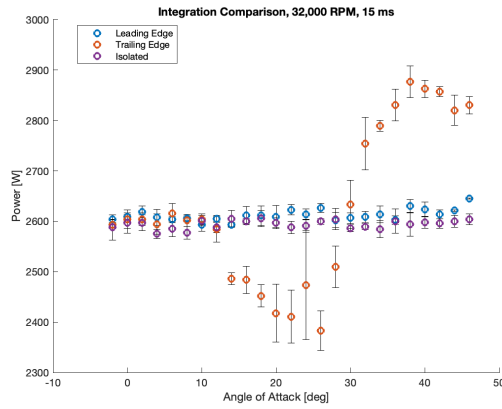


Figure C.47: Integration Comparison, 32,000 RPM, 15 ms7Comp<sub>Left</sub>



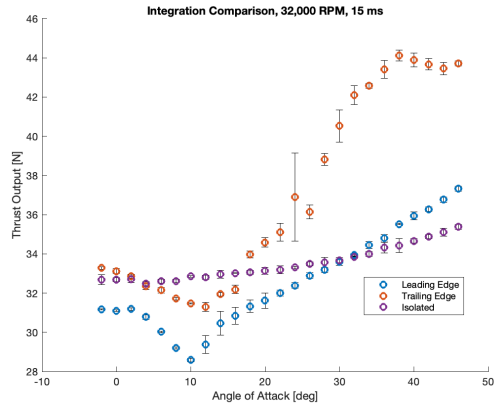


Figure C.48: Integration Comparison, 32,000 RPM, 15 msComp

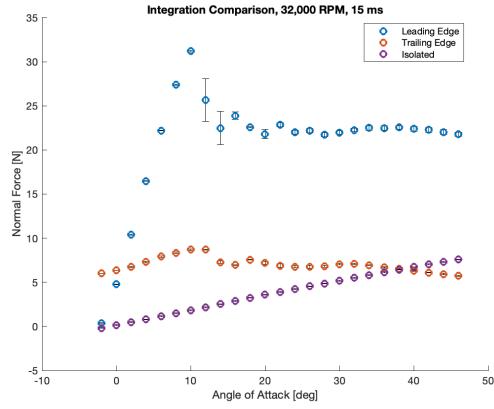


Figure C.49: Integration Comparison, 32,000 RPM, 15 msComp<sub>Lift</sub>

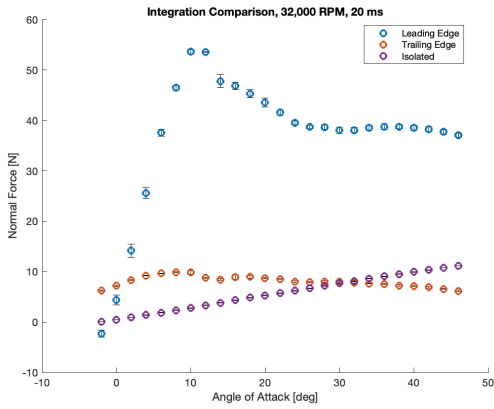


Figure C.50: Integration Comparison, 32,000 RPM, 20 ms1Comp<sub>Lift</sub>

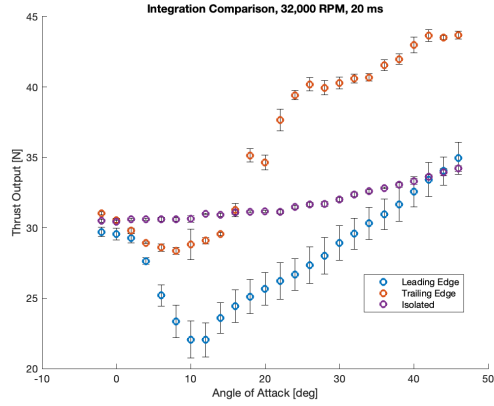


Figure C.51: Integration Comparison, 32,000 RPM, 20 ms3Comp

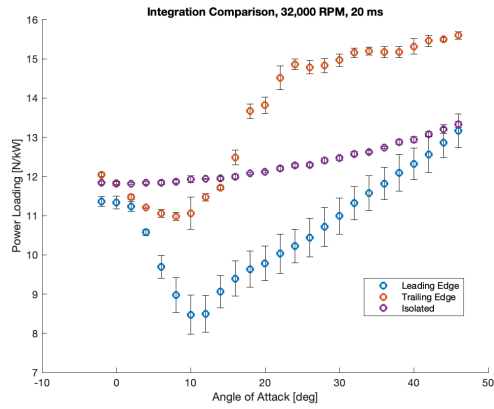


Figure C.52: Integration Comparison, 32,000 RPM, 20 ms3Comp<sub>P</sub>L

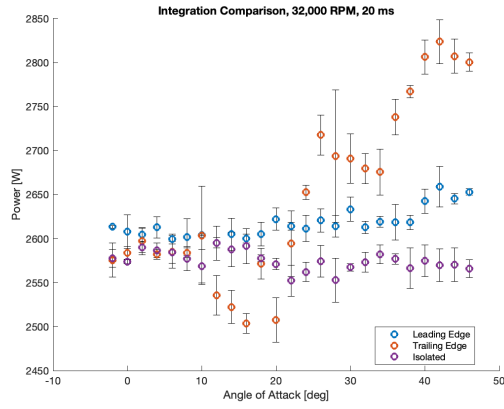


Figure C.53: Integration Comparison, 32,000 RPM, 20 ms  $7Comp_{lift}$

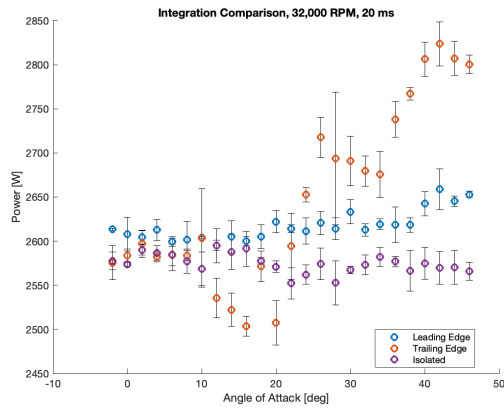


Figure C.54: Integration Comparison, 32,000 RPM, 20 ms  $7Comp_{pow}$

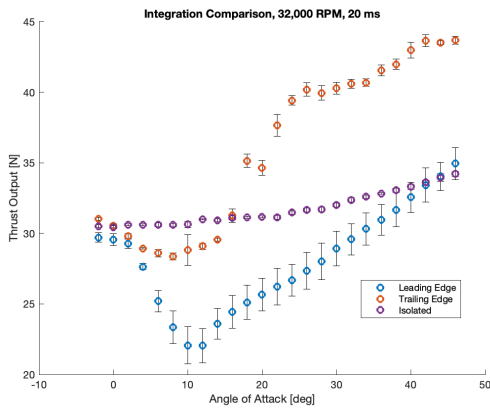


Figure C.55: Integration Comparison, 32,000 RPM, 20 ms  $Comp$

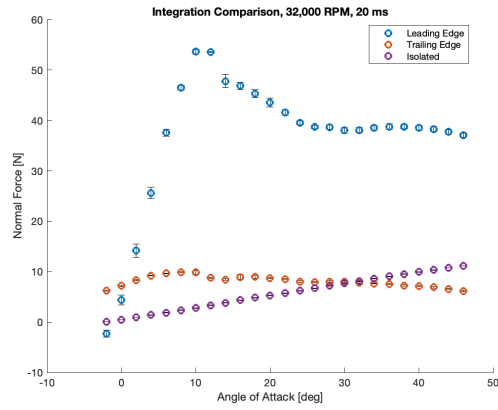


Figure C.56: Integration Comparison, 32,000 RPM, 20 ms  $Comp_{Lift}$

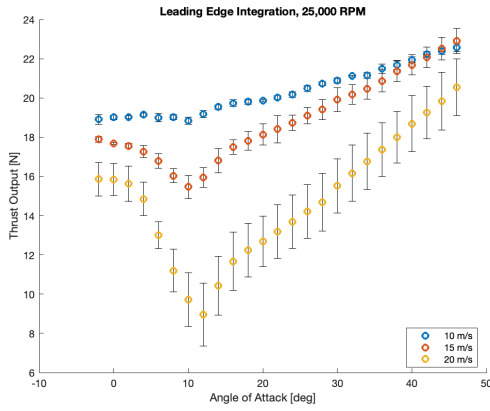


Figure C.57: Leading Edge Integration 25k Thr

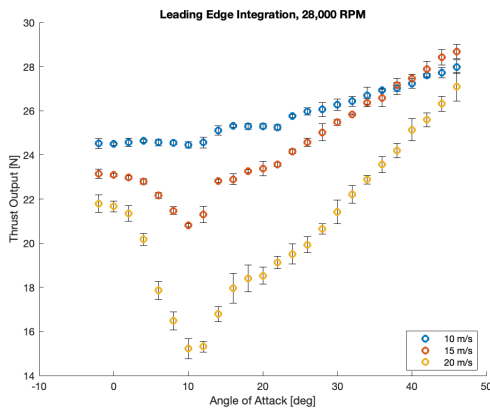


Figure C.58: Leading Edge Integration 28k Thr

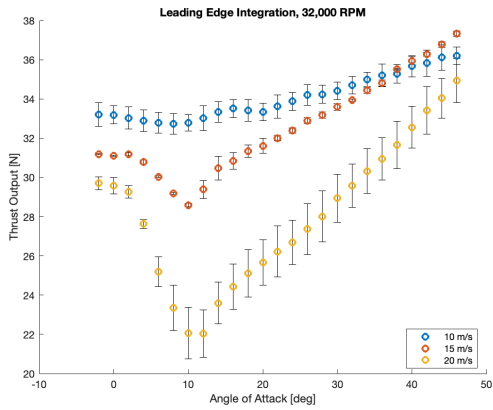


Figure C.59: Leading Edge Integration 32k Thr

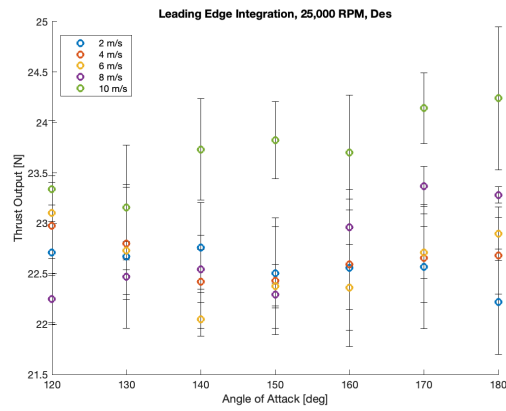


Figure C.60: Leading Edge Integration, 25,000 RPM, DesHov

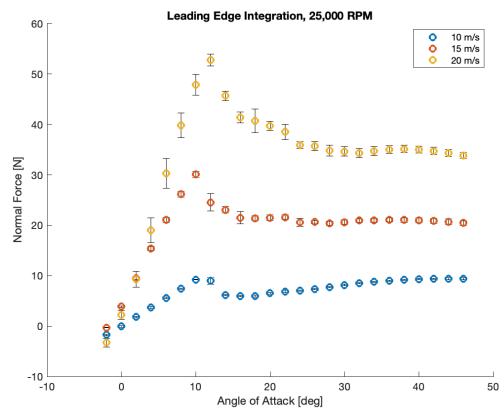


Figure C.61: Leading Edge Integration, 25,000 RPM1varair

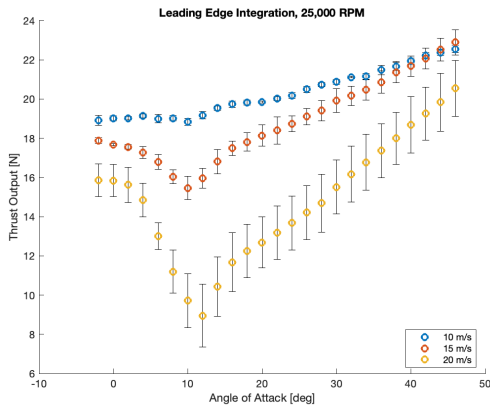


Figure C.62: Leading Edge Integration, 25,000 RPM3varair

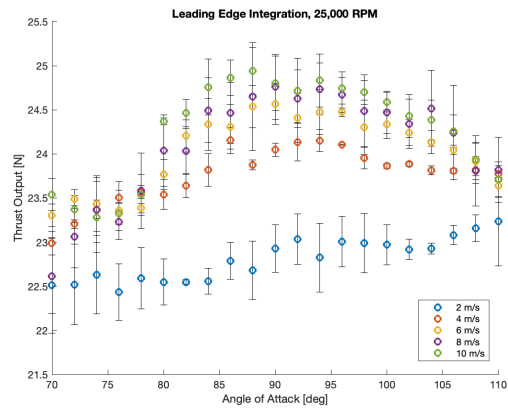


Figure C.63: Leading Edge Integration, 25,000 RPMHov

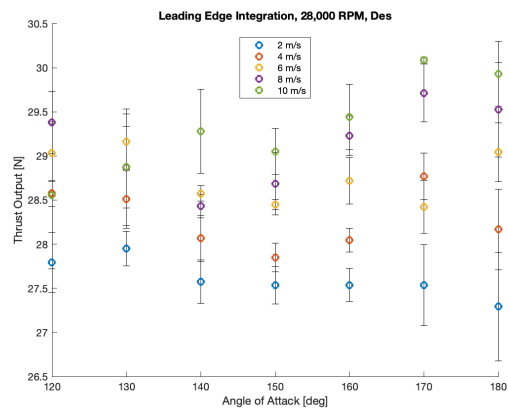


Figure C.64: Leading Edge Integration, 28,000 RPM, DesHov

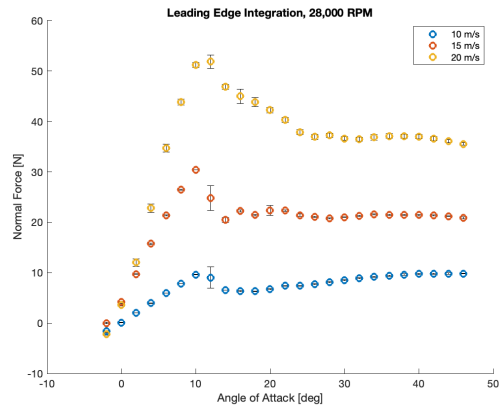


Figure C.65: Leading Edge Integration, 28,000 RPM1varair

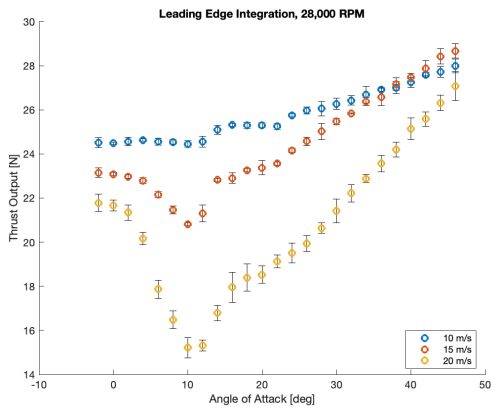


Figure C.66: Leading Edge Integration, 28,000 RPM3varair

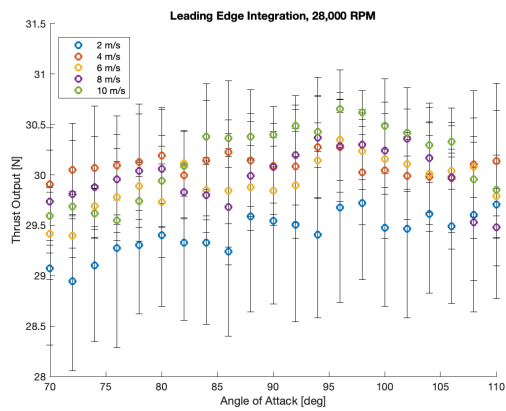


Figure C.67: Leading Edge Integration, 28,000 RPMHov

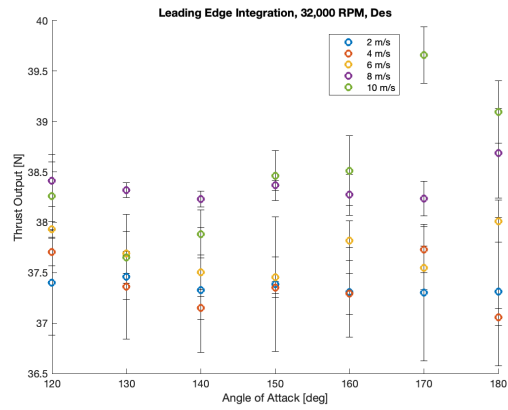


Figure C.68: Leading Edge Integration, 32,000 RPM, DesHov

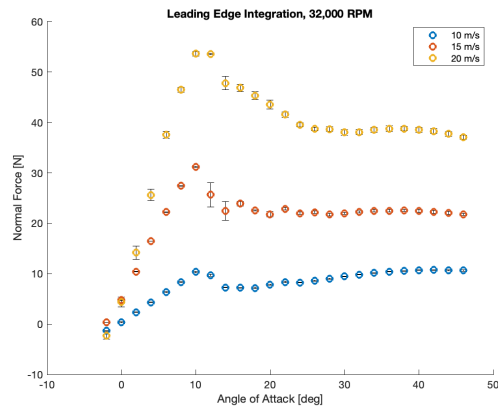


Figure C.69: Leading Edge Integration, 32,000 RPM1varair

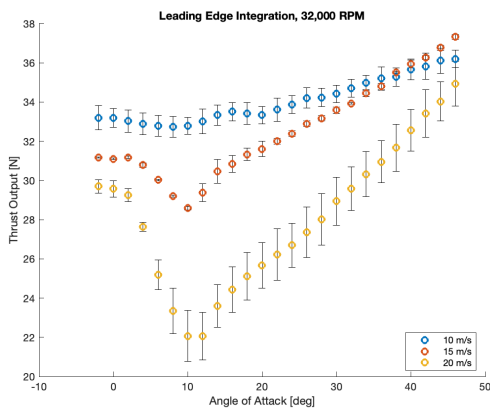


Figure C.70: Leading Edge Integration, 32,000 RPM3varair



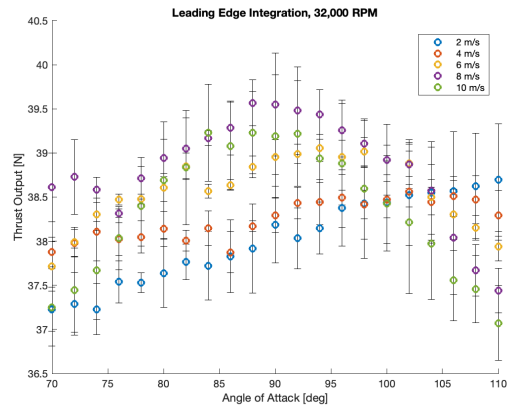


Figure C.71: Leading Edge Integration, 32,000 RPMHov

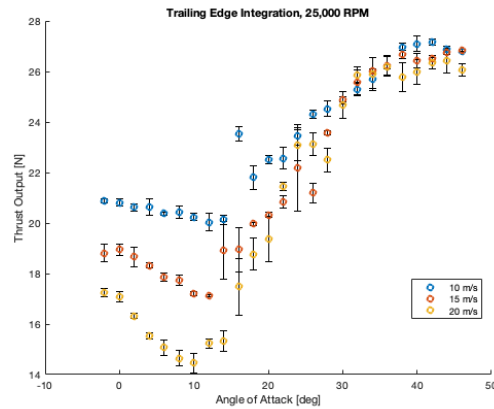


Figure C.72: Trailing Edge Integration 25k

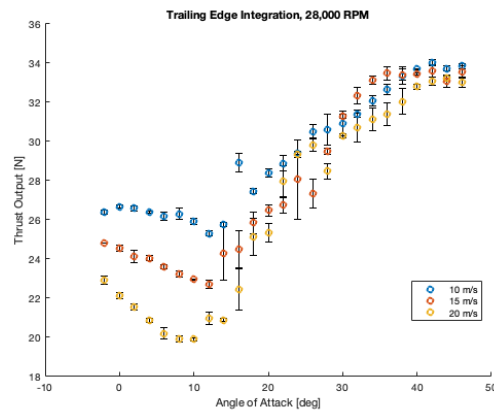


Figure C.73: Trailing Edge Integration 28k Thr

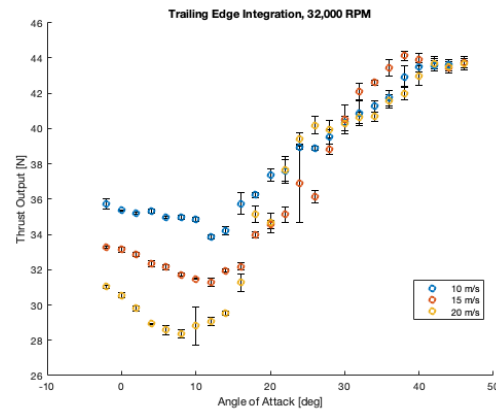


Figure C.74: Trailing Edge Integration 32k Thr

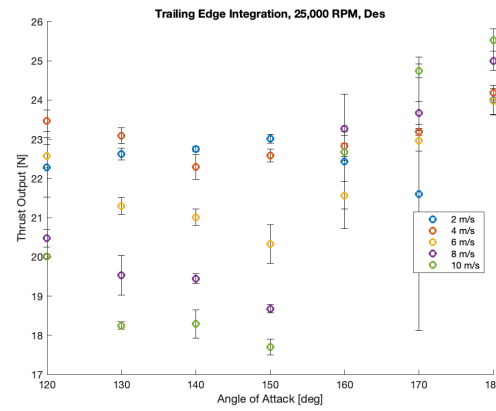


Figure C.75: Trailing Edge Integration, 25,000 RPM, DesHov

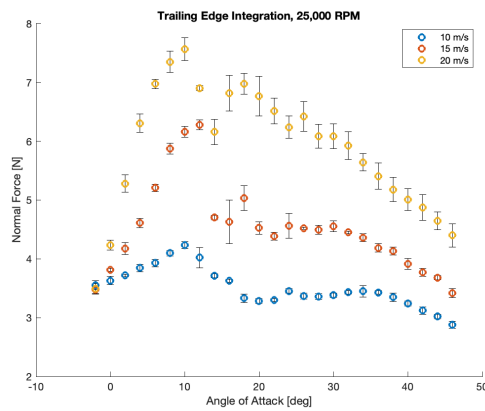


Figure C.76: Trailing Edge Integration, 25,000 RPM1varair

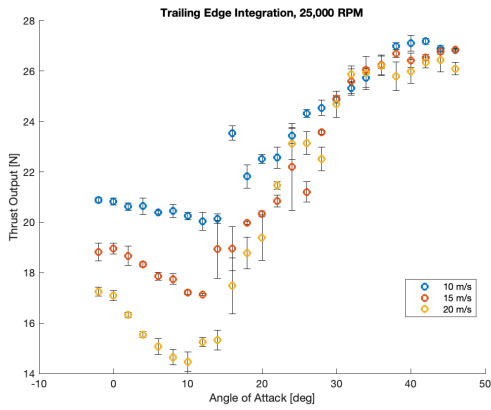


Figure C.77: Trailing Edge Integration, 25,000 RPM3varair

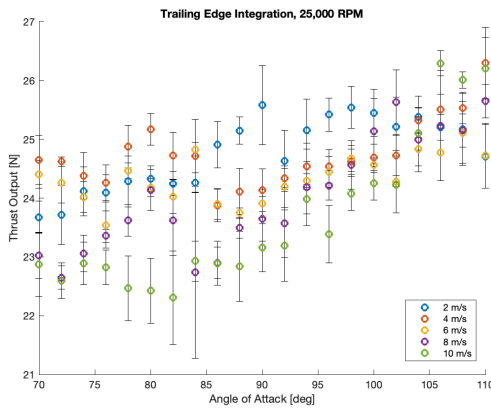


Figure C.78: Trailing Edge Integration, 25,000 RPMHov

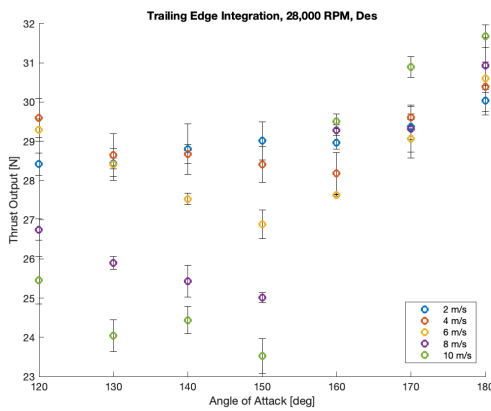


Figure C.79: Trailing Edge Integration, 28,000 RPM, DesHov

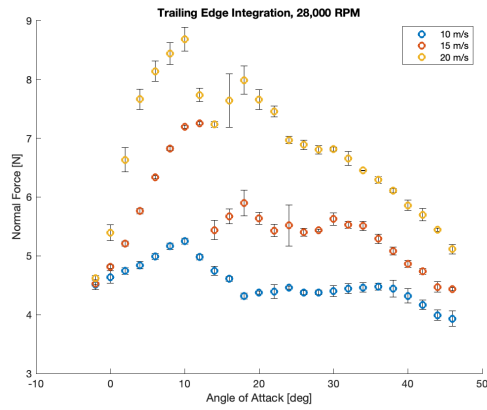


Figure C.80: Trailing Edge Integration, 28,000 RPM1varair

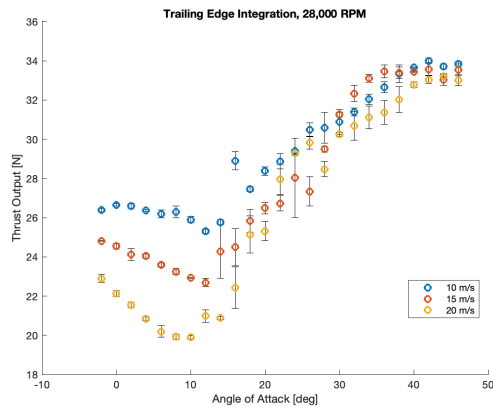


Figure C.81: Trailing Edge Integration, 28,000 RPM3varair

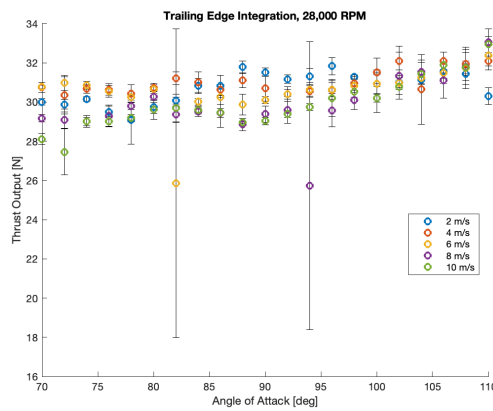


Figure C.82: Trailing Edge Integration, 28,000 RPMHov

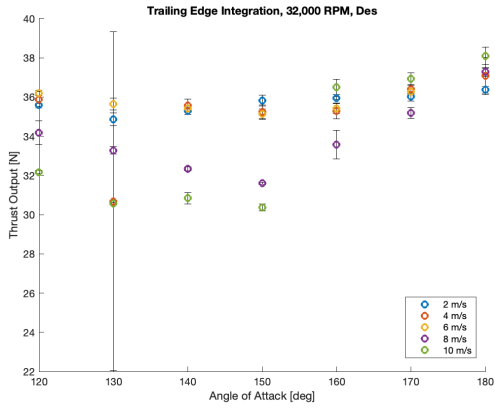


Figure C.83: Trailing Edge Integration, 32,000 RPM, DesHov

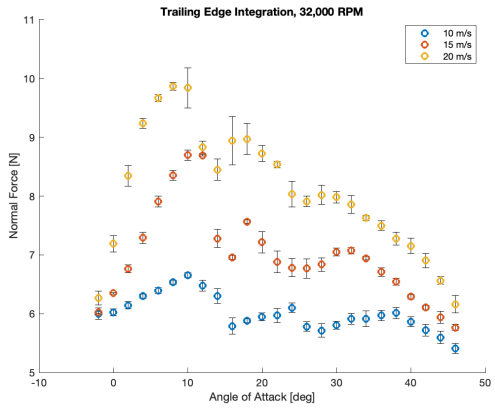


Figure C.84: Trailing Edge Integration, 32,000 RPM1varair

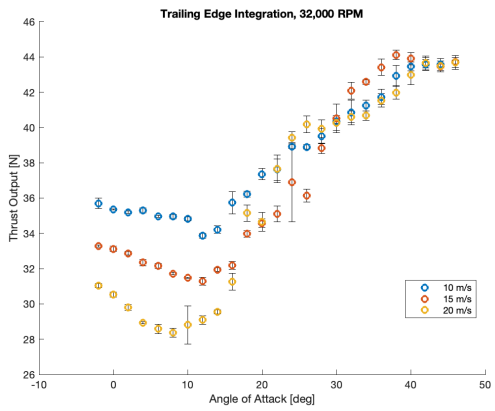


Figure C.85: Trailing Edge Integration, 32,000 RPM3varair

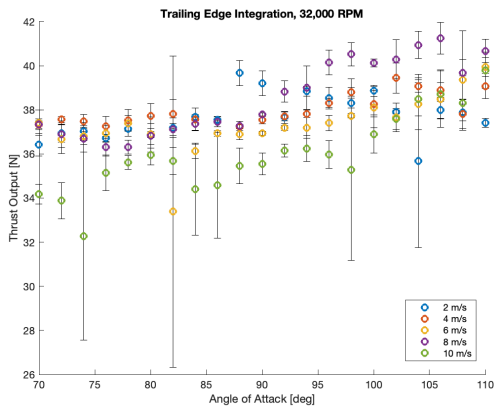


Figure C.86: Trailing Edge Integration, 32,000 RPMHov

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