Propeller and Propeller-In-Wing

Thrust Vectoring

Honors Thesis
Grace G. Culpepper
Department: Mechanical Engineering
Advisor: Sidaard Gunasekaran, Ph.D.
April 2021
Propeller and Propeller-In-Wing
Thrust Vectoring

Honors Thesis
Grace G. Culpepper
Department: Mechanical Engineering
Advisor: Sidaard Gunasekaran, Ph.D.
April 2021

Abstract
This research investigates the efficiency of a vane-based thrust vectoring system set in the wake of a propeller, supporting forward force at a minimum loss in net thrust. The vectoring system itself is placed in both a standalone propeller configuration and a propeller-in-wing configuration. Both static and wind-on force-based experiments are conducted at the University of Dayton Low Speed Wind Tunnel (UD-LSWT) with off-the-shelf R/C propellers. Sensitivity analysis determines both the effect of vane deflection angle on thrust vectoring and the effect of propeller placement with respect to the upper surface of the integrated wing on system performance. Static test results indicate notable improvement in vane performance when the vectoring design is placed in a wing. Thrust vectoring is achieved, along with subsequent changes in pitching moment, with incremental increases in vane deflection angle for two propeller pitch cases: 75° and 90°. Wind tunnel test results of the integrated propeller-in-wing system for the standard 90°-pitch orientation show successful thrust vectoring below the advance ratio of 0.3, which is practical for most relevant applications; the 75°-pitch orientation of the propeller-vane system observes thrust vectoring capabilities extending to an advance ratio of 0.7. Sensitivity analysis reveals that the overall efficiency of the propeller exposed to the flow freestream is greater than that of the propeller fully embedded in the mock wing though the embedded case features a better thrust vectoring capability.

Acknowledgements
Sincere appreciation and thanks go to the Henry Luce Foundation for support provided through the Clare Boothe Luce (CBL) research program. Another key benefactor, Mr. Jielong (Jacky) Cai, is extended much gratitude for his continued guidance throughout the duration of this work.
Table of Contents

Abstract 
Nomenclature 1
Introduction 2
Experimental Setup 9
General Setup 9
Standalone Propeller-Vane Thrust Vectoring Setup 10
Propeller-In-Wing Thrust Vectoring Setup 12
Test Matrix 15
Static Testing 15
Wind-On Integrated Propeller-Wing Testing 17
Results 19
Static Testing Results 19
Wind-On Testing Results 26
Conclusions 39
References 41

Table of Figures

Figure 1. a) AgustaWestland Project Zero [3] with wing embedded propulsion system b) Ryan XV-5 [4] with fan-in-wing propulsion system
Figure 2. Axial and side thrust coefficient trends with changing vane tilt angle for static and wind-on conditions tested by Harinarain. [10]
Figure 3. Experimental results showing the connection between pitching vane deflection and hover pitching moment for variable ducted fan configurations studied by Weir. [12]
Figure 4. Induced lift variation with advance ratio for a set of fan-in-wing designs as published by Deckert. [8]
Figure 5. Fan-in-wing model studied by Hickey and Ellis with a) inlet vanes and b) exit vanes.
Figure 6. Relationship between exit vane tilt angle and a) pitching moment coefficient and b) total lift coefficient for integrated wing design as studied by Hickey and Ellis.
Figure 7. a) Sketch of ducted propeller-vane test setup indicating the relationship between force components and propeller wake. b) Experimental setup of the square duct-vane propulsion system used for static testing. .................................................................10
Figure 8. Section view of sensor testing configurations designed to measure forces acting on a) the propeller-vane assembly and b) the propeller alone. .................................................................11
Figure 9. a) Internal assembly of the propeller-in-wing test setup. b) Aerial view of mounted propeller-in-wing setup and b) isometric view of propeller-in-wing test setup.........................13
Figure 10. a) Side view of the exposed propeller and b) side view of the embedded propeller placement sensitivity cases. ..................................................................................14
Figure 11. a) Standard 90° propeller pitch orientation and b) 75° propeller pitch orientation of the PV system. ...........................................................................................................14
Figure 12. a) Thrust coefficient and b) power coefficient comparisons for baseline APC 11x7 propeller cases from various studies. .................................................................16
Figure 13. a) FFT analysis of experimental frequency inputs. Experimental data readings before and after FFT-based filtration for the b) force and c) torque of a bare propeller rotating at 100 RPS. ...........................................................................................................17
Figure 14. Comparing propeller rotational speed and a) axial thrust coefficient and b) power coefficient across iterations when δv = 0°. .................................................................20
Figure 15. a) Normal force coefficient and b) pitching moment coefficient of all experimental setups across vane deflection angles. .................................................................22
Figure 16. Axial thrust coefficient of all static experimental setups across vane deflection angles. ...........................................................................................................23
Figure 17. Deflection and thrust efficacies, ηb and ηr, with respect to vane deflection angle for all configurations under hover conditions. .................................................................25
Figure 18. The overall propeller-vane efficacy ηb with respect to vane deflection angle for all configurations under hover conditions.................................................................25
Figure 19. Normal thrust coefficient values across advance ratio conditions for a) a bare propeller and b) a bare propeller integrated in a mock wing pitched to facilitate the effective deflections noted. ...........................................................................................................27
Figure 20. Axial thrust coefficient values across advance ratio conditions for a) a bare propeller and b) a bare propeller integrated in a mock wing pitched to facilitate the effective deflections noted. ...........................................................................................................28
Figure 21. Normal thrust coefficient across advance ratio conditions for different vane deflection angles for PVW at 90°-pitch orientation.................................................................29
Figure 22. Normal thrust coefficient across advance ratio conditions for different vane deflection angles for PVW at 75°-pitch orientation.

Figure 23. Drag force experienced by different configurations across variable advance ratio conditions: for PVW, $\delta_v=0^\circ$ (embedded propeller).

Figure 24. Side and underside views of flow visualization of PVW system (embedded propeller) at $\delta_v=0^\circ$ and $J = 0.2$.

Figure 25. Propeller pitching moment coefficient across advance ratio conditions for different vane deflection angles for PVW at 90°-pitch orientation.

Figure 26. Propeller pitching moment coefficient across advance ratio conditions for different vane deflection angles for PVW at 75°-pitch orientation.

Figure 27. Axial thrust coefficient across advance ratio conditions for different vane deflection angles for PVW at 90°-pitch orientation.

Figure 28. Axial thrust coefficient across advance ratio conditions for different vane deflection angles for PVW at 75°-pitch orientation.

Figure 29. Overall thrust vectoring efficiency of a bare propeller in wing across advance ratio conditions for different effective deflections varied with propeller pitch.

Figure 30. Overall thrust vectoring efficiency of all PVW iterations across changing advance ratio conditions for different effective vane deflection cases.

Table of Tables

Table 1. Static Test Matrix Including All Test Iterations

Table 2. Dynamic Test Matrix Including All Test Iterations

Table 3. Effective Vane Deflection Derived from PV Orientation and Initial Vane Deflection Angles
Nomenclature

\( C_D \) = Drag Coefficient
\( C_T = \text{Propeller Thrust Coefficient}; \quad C_T = \frac{T}{\rho n^2 D^4} \)
\( C_Q = \text{Propeller Torque Coefficient}; \quad C_Q = \frac{P}{\rho n^3 D^5} \)
\( C_P = \text{Propeller Power Coefficient}; \quad C_P = 2\pi C_Q \)
d = Propeller Diameter, (m)
D = Drag Force (N)
J = Propeller Advance Ratio; \quad J = \frac{U_\infty}{nD}
n = Rotational Speed per Second
\( \eta = \text{Propeller Efficiency/Efficacy} \)
P = Power, (W)
Q = Torque (Nm)
T = Thrust (N)
\( V_\infty = \text{Freestream Velocity, (m/s)} \)
\( V_{\text{local}} = \text{Local Velocity at Propeller, (m/s)} \)
\( \theta = \text{Propeller Forward Pitch Angle (deg)} \)
\( \delta_V = \text{Vane Deflection Angle (deg)} \)
\( \gamma = \text{Propeller Pitch, (m)} \)
\( \rho = \text{Air Density, (kg/m}^3) \)

Subscripts:
\( Z = \text{Propeller Axial Force} \)
\( X = \text{Propeller Side Force} \)
\( Y = \text{Propeller Normal Force} \)
e = Effective Propeller Wake Deflection Angle
\( \theta = \text{Vane Angular Deflection} \)
TV = Thrust Vectoring
T\delta = Thrust Vectored by Vane
Introduction

Commercial interest in personal air vehicles (PAV) and unmanned air vehicles (UAV) featuring vertical takeoff and landing capabilities for mobile air transportation has grown significantly in recent years. Several propulsors have been considered as a primary source for thrust and lift in such vehicles including fixed pitch multi-rotors and distributed electric and wing-embedded propulsion systems. While a multi-rotor system offers superior hover performance, its efficiency in forward flight is relatively low compared to that of fixed-wing aircraft [1-2]. Wing-embedded propulsion (WEP) systems and fan-in-wing systems like that of the AgustaWestland Project Zero (Figure 1a [3]) and Ryan XV-5 Vertifan (Figure 1b [4]) have been widely considered as potential alternatives to multi-rotor systems, providing higher cruise efficiency. Unlike the multi-rotor, the WEP system features a greater forward flight efficiency by allowing wings to generate much of the lifting force, thus reducing the operational cost of the design [1-2]. Despite the merits of such competing setups, one advantage maintained by the multi-rotor system is that of added maneuverability provided through differential thrust components which are absent in fixed-wing-type UAVs with wing-embedded or distributed electric propulsion (DEP).

![Figure 1. a) AgustaWestland Project Zero [3] with wing embedded propulsion system b) Ryan XV-5 [4] with fan-in-wing propulsion system.](image)

One possible solution to increase the maneuverability of fan-in-wing propulsion designs while maintaining higher cruise efficiency is to add a set of vanes in the wake of the present propellers to vector thrust. Through this design modification, a set of vanes positioned behind the
propeller redirects the high energy wake, thereby achieving thrust vectoring. The vanes may also reduce the swirl component in the wake, increasing thrust efficiency [5-6]. In the mid-1960s, the U.S. Army and General Electric conducted a thorough investigation into state-of-the-art fan-in-wing technology through the Ryan XV-5, a jet-powered single-pilot aircraft. Flight tests examined the experimental design to assess maneuverability, noise footprint, steep terminal approach, and V/STOL performance. Historical reviews by Corgiatan et al., Deckert, and Gerdes [7-9] on the XV-5 noted that, though such systems reliably maintain gas-driven lifting, their performance in the transition to forward flight remains non-ideal due to a notably weak low-speed directional control response and complicated power management. This operational drawback could be mitigated using more modern flight control systems, thus presenting an opportunity to revisit fan-in-wing designs and develop a vane-based thrust vectoring system for modern PAV and UAV application.

A study done by Harinarain [10] and Bento [11] investigated two airfoil-shaped (NACA 0012) vanes behind a propeller disk, one aligned vertically and the other horizontally, designed to provide pitch and yaw control. Static experimental results from Harinarain are shown in Figure 2. The propeller disk was placed perpendicular to the freestream; thus, the axial thrust coefficient $C_{Tz}$
describes forward thrust performance, and propeller normal thrust coefficient $C_{Ty}$ represents vectored thrust which provides pitch control. In general, axial thrust $C_{Tz}$ decreases while vectored thrust $C_{Ty}$ increases with the incremental change in vane angle under both static and wind-on conditions. Noticeable increment in the vectored thrust $C_{Ty}$ corresponded to the change of vane tilt angle up to 20° for the static case though the coefficient remained constant for subsequent changes in tilt, likely a byproduct of vane stall. For the wind-on experiment, a higher increment in the vectored thrust coefficient was observed under higher rotations-per-minute (RPM) cases corresponding to a lower advanced ratio. These results indicate the potential benefit of using a vane-based thrust vectoring system at small advance ratios which is the likely operational condition for most UAV and PAV.

A study of free-flying ducted propeller designs completed by Weir [12] used a vane control system similar to that proposed in this study to provide triaxial stability control. Weir’s development of a free-flying ducted propeller system included wind-tunnel testing of six variable designs under subsonic conditions, measuring in particular changes in performance due to vane deflection and duct pitch. Across test conditions, designs were placed at variable angles of attack to study the transition performance from hovering to forward flight. Configurations 1, 2, and 3 were tied together in basic design, an annular duct with a diffuser; the first had round structural supports downstream of the control vanes, the second did not have these supports so their effect might be quantified, and the third built off of the second with an adjustment in diffuser angle to reduce flow separation. Configurations 4 and 5 included a torus rather than airfoil inlet geometry, the fourth otherwise mimicking configuration 2 to isolate the effects of lip geometry changes and the fifth removing the diffuser feature to assess the importance of the diffuser itself. Configuration 6 was built from the same footprint as configuration 3 with an extension to the diffuser to shield the vanes in the duct from effects of jet bending and stall. Each of the six configurations, with different inlet duct geometries, fan support structures, and exit diffuser designs incorporated a set of NACA 0018
pitching vanes placed in the propeller wake. Figure 3 below shows the experimental results of vane deflection on the hover pitching moment of the system for the first five of Weir’s configurations; the sixth is excluded as its diffuser extension marks the design as dissimilar to that of the present investigation. Results indicate a high effectiveness of the control vanes in influencing the system’s pitching moment across the range of deflection angles tested, -20° to 30°. Moreover, the linear trend of changes in pitching moment indicates a higher stall angle condition for these exit vanes compared to the usual stall angle of the same NACA 0018 airfoil in fixed wing studies.

Figure 3. Experimental results showing the connection between pitching vane deflection and hover pitching moment for variable ducted fan configurations studied by Weir. [12]
Deckert [8] examined a range of WEP design configurations under both static and dynamic conditions. Model 2 (annotated in Figure 4) includes a large fan integrated in a wing for lift production while Models 4 and 6 have smaller fans integrated to provide rolling and pitching moment control, respectively. In Figure 4, the fan-in-wing induced lift, $L_i/T_s$, which is the ratio of the lift induced by the integrated fan to the total thrust generated by the fan, is shown for a range of advance ratios. Advance ratio was changed in this case by adjusting the airspeed conditions for the system tests. In most cases, placing a rotor in the wing resulted in a positive effect on lift generation, the exception found in Model 6c which placed its fan closer to the leading edge of the wing, causing a reduction of the flow speed over the upper wing surface.

![Figure 4. Induced lift variation with advance ratio for a set of fan-in-wing designs as published by Deckert. [8]](image)

Hickey and Ellis [13] investigated the performance of a semi-span wing featuring an embedded fan with both inlet and exit vanes acting independently as shown in Figure 5. A NACA 16-015 wing profile was used for the 12.5-square-foot wing area, and a duct of 1.63-foot diameter was placed inside the wing’s 2-foot chord. All 15 exit vanes of the ducted fan featured a NACA 65-010 airfoil profile. Wind tunnel tests maintained a constant wind tunnel pressure, $q_{∞}$, and propeller speeds were varied between 0-8000 RPM. In this study, it was concluded that exit vanes
could be used to generate a net propulsive force for the attached system while operating in a range of freestream velocities with only a small reduction in lift. Inlet vanes, by contrast, caused no measurable change in static lift when individually manipulated to maintain flow attachment. When all inlet vanes were axially aligned, static lift was indeed increased – along with power requirements. Thus, though inlet vanes did show potential in reducing nonuniform propeller inflow, each vane would need to be independently adjusted with forward speed to provide a performance gain rather than a loss. Exit vanes may then be considered as a viable option for thrust generation in forward flight, reducing static lift and increasing necessary power supply only slightly under such conditions. Figure 6 below highlights published results of the study where the following equations define each coefficient:

\[
C_F = \frac{L_{propeller}}{q_\infty S} \quad (1)
\]

\[
C_Q = \frac{Q}{q_\infty S} \quad (2)
\]

\[
C_L = \frac{L_{total\ wing}}{q_\infty S} \quad (3)
\]

Figure 5. Fan-in-wing model studied by Hickey and Ellis with a) inlet vanes and b) exit vanes. [13]
Figure 6. Relationship between exit vane tilt angle and a) pitching moment coefficient and b) total lift coefficient for integrated wing design as studied by Hickey and Ellis. [13]

This review of literature provides reasonable grounds for confidence in effective thrust vectoring from exit vanes, equally capable of influencing system pitching moment at relatively low cost to the lift or static thrust for the system in which they are set. Historically, most literature considers a lifting fan rather than a standalone propeller. Due to increased use of R/C and sport propellers in UAVs, air taxis, and the like, this study examines the effect of thrust vectoring vanes on a propeller-based system, graduating in later iterations to an integrated propeller-in-wing design.
Experimental Setup

General Setup

Experiments were conducted on a thrust-stand at the University of Dayton Low Speed Wind Tunnel lab (UD-LSWT). An APC 11-inch (279.4 mm) by 7-inch (177.8 mm) thin electric propeller was employed for all design iterations considered because of the abundance of available results published with the same propeller selection in comparable literature data references [19-20]. The propeller was driven by an OMA-3810-1050 brushless out-runner electric motor, powered by a PSW 30-108 constant-voltage supply. The peak Reynolds number achieved by the propeller blades was 78,000, calculated based on the blade chord at 70% blade-semi-span for the peak propeller rotational speed tested. The propeller rotational speed range itself, with its lower bound derived from signal-to-noise considerations and upper bound limited by the speed control capacity, was 60-120 RPS.

The propeller and motor described were attached to an ATI Industrial Automation Mini-40 six-component force balance (www.ati-ia.com) [14]. Axial thrust describes the force acting along the Z-axis of the sensor, while vectored thrust considers the force observed along the Y-axis of the sensor. The propeller torque corresponding to pitching moment is thus the rotational moment about the X-axis. The force balance bolts to an aluminum-extrusion frame, itself secured to the UD-LSWT lab floor and wind tunnel contraction. The balance has a maximum tolerance of 120-Newton’s (N) force on its Z-axis and maximum torque of 2 Nm about its X-axis. The peak thrust and torque encountered in practice were 12 N and 0.25 Nm, respectively. The data sampling rate for the sensor was maintained at 1,000 Hz for a 15-second duration for each testing condition with two runs per each to improve data repeatability. In an effort to minimize sensor drift, tare values were taken before and after each test. The average of the two tares was then subtracted from the respective thrust and torque readings to correct for said drift. A band-pass filter was used for the
data post-processing, filtering out noisy frequencies related to propeller rotational speed and the natural frequency of the thrust stand.

**Standalone Propeller-Vane Thrust Vectoring Setup**

For static testing of the standalone propeller-vane setup, four 76.2-mm chord vanes were made with a NACA 0012 airfoil section. The fundamental relationship between deflection of these vanes and vectored thrust is shown in Figure 7a below. The vane deflection (tilt) angle $\delta_v$ was locked in place by a rigid fixture which altered physically each time a different vane deflection angle was tested. The tip of each vane connected to a square duct sheath (shown in Figure 7b) to eliminate vane tip vortices. The square duct-vane setup was then bolted on 80-20 aluminum extrusion frame, itself secured to the lab floor and test section inlet. The rotational speed of the propeller was measured by a laser mounted to the lab ceiling, the signal therefrom collected by a photodiode mounted beneath the propeller-vane setup as shown. The propeller-vane (PV) setup was placed at least one propeller diameter away from any type of blockage to minimize the error related to experimental setup [15].

![Figure 7](image)

**Figure 7.** a) Sketch of ducted propeller-vane test setup indicating the relationship between force components and propeller wake. b) Experimental setup of the square duct-vane propulsion system used for static testing.
Force-based testing was conducted using two different sensor interface configurations within the PV system. The first configuration was designed to measure the overall force experienced by the propeller-vane system. The second configuration was designed to isolate the forces experienced by the propeller in order to quantify the effect of the vanes on propeller performance, particularly those of the power and torque coefficients. Schematics of these two force balance configurations are shown in Figure 8. Again, the primary difference between these two configurations is the strategic placement of the force balance to measure firstly forces of the total propeller-vane system and secondly those of the propeller alone.

![Figure 8](image)

Figure 8. Section view of sensor testing configurations designed to measure forces acting on a) the propeller-vane assembly and b) the propeller alone.
Propeller-In-Wing Thrust Vectoring Setup

The propeller-in-wing experiments were conducted at the UD-LSWT with the tunnel in an open jet configuration. The UD-LSWT has a 16:1 contraction ratio, 6 anti-turbulence screens, and a 762-mm by 762-mm open jet test section. The effective length of the test section is 1829 mm. Per the tunnel design, a 1118-mm by 1118-mm collector accepts the expanded air on its return to the diffuser. The freestream turbulence intensity is 0.1% at 15 meters-per-second (as measured by hot-wire anemometry). A pitot tube connected to a TSI T600 Micromanometer was used to measure the freestream velocity during experiments.

The standalone propeller-vane thrust vectoring test setup shown in Figure 7 of the previous section was moved inside a mock wing, built with a span of 833.2 mm and a chord length of 609.6 mm, for dynamic testing. This setup is described as the propeller-vane-in-wing (PVW) design throughout this documentation. The wing section itself was constructed using an Eppler 479 airfoil profile, selected for its symmetry and thickness, properly encasing the propeller-vane system. A series of wooden ribs with aforementioned Eppler 479 profile were laser cut and connected by leading edge and trailing edge spars made of 80-20 aluminum railing. The rib and spar structure of the wing was covered with a MonoKote [16] film thereafter to form the skin thereof. The internal PV assembly along with the fully integrated PVW system are shown in Figure 9.

Following construction, the wing was secured to the test section inlet as shown in Figure 9c. A square opening of 292.1-mm length was allocated to house the propeller-vane system. The center alignment of the propeller and sensor was positioned at the chord location featuring maximum wing thickness (35% of the chord length); this placement has been shown to support ideal performances for wing lift generation [17]. The mock wing mount was fixed in isolation from the propeller-vane propulsion system so that force-based testing would only quantify interactions relevant to the PV system rather than lift, pitching moment, etc., generated by the wing.

Compared to the vane chord length selected for the study by Harinarain and Bento [10,11], this investigation incorporated a more significant vane chord, normalized at 28% of the propeller
diameter, to optimize the thrust vectoring performance of said vanes. Furthermore, expanding on the simple settings of prior publications, differences in system performance due to variable propeller-vane placements were studied here; one case with the propeller embedded in the wing (vanes exposed to the freestream) and one with the propeller exposed to the freestream (vanes embedded in the wing) appear. These two propeller configurations are highlighted in Figure 10.

Figure 9. a) Internal assembly of the propeller-in-wing test setup. b) Aerial view of mounted propeller-in-wing setup and b) isometric view of propeller-in-wing test setup.
Beyond propeller placement investigation, further testing examined the effects of forward propeller pitch on system performance. The entire PV system was directed 15° forward into the freestream flow to facilitate a 75° pitch angle. The location of the propeller hub was maintained constant for both pitch conditions, matching that of the embedded propeller for a 90°-pitch case. As the 75°-pitch case required partial exposure and embedment of the APC 11x7 propeller itself, the propeller location sensitivity analysis was not incorporated into analysis of the altered orientation. Both the standard 90°-pitch and 75°-pitch orientations are shown in Figure 11 below.

Figure 11. a) Standard 90° propeller pitch orientation and b) 75° propeller pitch orientation of the PV system.
Test Matrix

Static testing – wind-off with no incoming freestream flow, designed to resemble vertical takeoff and landing (VTOL) and hovering conditions for aircraft – as well as dynamic testing – wind-on with an incoming freestream introduced, designed to resemble forward flight conditions – are key to this study. The test matrix for each condition is discussed in this section.

Static Testing

Static tests were purposed to examine the performance of the standalone propeller-vane system as well as the propeller-vane system embedded in a wing (PVW). A standalone bare propeller and a bare propeller integrated into a mock wing were tested to serve as baselines for these static experiments, the first useful in identifying performance effects observed from PVW integration and the second useful for identifying effects from the thrust vectoring design alone.

To verify the reliability of the propeller test stand, bare propeller static testing results from the present study were compared to the UIUC database [18] as well as two previous UD-LSWT studies conducted by Cai et al. [19] & Gunasekaran et al. [20]. The comparison of the thrust and power coefficients is shown in Figure 12. The error bars included in this plot represent a 95% confidence interval for the results of the current study following noise filtration. For both thrust coefficient and power coefficient, experimental data of the current study is shown as comparable to experimental results of both previous UD-LSWT studies and the UIUC database, providing confidence in the current test setup. These results indicate a slight increment of $C_T$ with bare propeller rotational speed due to the Reynolds number effects while the $C_P$ remains relatively constant across the tested RPM range.

Fast Fourier transform (FFT) analysis applied to the raw experimental data identified the dominant frequencies impacting sensor readings. These frequencies, along with that matching the active propeller rotation, were then mitigated in raw results via use of a band-pass filter. The FFT plot for a sample data case is shown highlighting dominant frequencies in Figure 13a, and the
experimental force and torque results before and after aforementioned filtration are shown in Figure 13b and Figure 13c respectively.

Table 1. Static Test Matrix Including All Test Iterations

<table>
<thead>
<tr>
<th>Test Cases</th>
<th>Propeller</th>
<th>Propeller Rotational Speed (RPS)</th>
<th>Propeller Reynolds Number</th>
<th>Vane Deflection Angle $\delta_V$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare propeller</td>
<td>APC 11x7</td>
<td>60-120</td>
<td>35,000-78,000</td>
<td>N/A</td>
</tr>
<tr>
<td>Bare propeller in wing</td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Standalone propeller-vane system (SA PV)</td>
<td></td>
<td></td>
<td></td>
<td>0, 5, 10, 15, 20, 30</td>
</tr>
<tr>
<td>90°-pitch propeller-in-wing system (PVW) (embedded, exposed)</td>
<td></td>
<td></td>
<td></td>
<td>0, 5, 10, 15, 20, 30</td>
</tr>
<tr>
<td>75°-pitch propeller-in-wing system (PVW)</td>
<td></td>
<td></td>
<td></td>
<td>-20, -10, 0, 10, 20</td>
</tr>
</tbody>
</table>

Figure 12. a) Thrust coefficient and b) power coefficient comparisons for baseline APC 11x7 propeller cases from various studies.
Figure 13. a) FFT analysis of experimental frequency inputs. Experimental data readings before and after FFT-based filtration for the b) force and c) torque of a bare propeller rotating at 100 RPS.

Wind-On Integrated Propeller-Wing Testing

The test matrix for the wind-on, propeller-in-wing (PVW) tests is shown in Table 2. For the 90° pitch orientation, the two aforementioned propeller placements were tested with fixed propeller rotational speed. The 75° pitch orientation testing came thereafter. Different advance ratios were achieved by changing the freestream velocity of the wind tunnel section from 0 – 19 m/s. Motor power output was adjusted as necessary to maintain a constant propeller rotational speed for all tunnel speed conditions. Two trials were completed for each experimental iteration to check for data repeatability.
<table>
<thead>
<tr>
<th>Test Case</th>
<th>Propeller Location</th>
<th>Propeller Rotational Speed (RPS)</th>
<th>Advance Ratio, J</th>
<th>Wind Tunnel Speed (m/s)</th>
<th>Vane Deflection Angle $\delta_V$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare propeller</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Bare propeller in wing</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>90°-pitch propeller-in-wing system</td>
<td>Embedded</td>
<td>100</td>
<td>0 - 0.7</td>
<td>0 - 19</td>
<td>0, 10, 20, 30</td>
</tr>
<tr>
<td></td>
<td>Exposed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75°-pitch propeller-in-wing system</td>
<td>Embedded equivalent</td>
<td></td>
<td></td>
<td></td>
<td>-20, 10, 0, 10, 20</td>
</tr>
</tbody>
</table>
Results

The experimental results for this propeller-based thrust vectoring study are split into two distinct sections. The first consists of results from the static testing of the standalone propeller-vane system (SA PV) and the propeller-in-wing system (PVW). These results show the performance of the thrust vectoring propeller-vane system during vertical takeoff, hovering, and transition to forward flight. The second section consists of results from the wind-on testing of propeller-in-wing system (PVW) which describe the performance of the thrust vectoring system during forward flight across advance ratio conditions.

Static Testing Results

Experimental results for axial thrust coefficient $C_{Tz}$ and power coefficient $C_p$ are shown below in Figure 14 for the bare propeller, standalone propeller-vane system (SA PV), the propeller-in-wing system (PVW) with propeller embedded and exposed at a 90° pitch, and the PVW system at a 75° pitch. All of the vectoring vanes were set to a zero-degree deflection ($\delta_v = 0°$) for both PVW systems.

The differences between the bare propeller and the standalone propeller-vane system describe the effect of vanes and the square sheath on the propeller performance; the differences between the standalone propeller-vane system and the propeller-in-wing system indicate the effect of the wing enclosure on the propeller performance. It should be noted that the results shown in Figure 14 were obtained using the second configuration of the propeller-vane-sensor interface shown in Figure 8 where only the forces experienced by the propeller are measured. The results indicate a 4% reduction of total axial thrust for the propeller-vane system due to the drag force acting on the vanes and sheath for the SA PV setup and an additional 6% of loss in axial thrust due to wing enclosure effects for the PVW setup.

In terms of power, the change in consumption became negligible when placing the vane system in the propeller wake. An average incremental difference of 3% was observed between the
standalone and integrated propeller-vane systems due to the wing interference when placing the system therein.

**Figure 14.** Comparing propeller rotational speed and a) axial thrust coefficient and b) power coefficient across iterations when $\delta_V = 0^\circ$.

An effective vane deflection angle $\delta_{Ve}$ is used to compare deflection cases from the two propeller pitch orientations, $\theta = 90^\circ$ and $\theta = 75^\circ$. The $\delta_{Ve}$ value is defined as follows:

$$\delta_{Ve} = \delta_V + (90 - \theta)$$

(4)

The effective deflection angle for each case tested is shown below in Table 3.

The normal force and pitching moment generated by the propeller-vane system at different vane deflection angles are shown in Figure 15. Examining first the $90^\circ$-pitch orientation cases, an increment in normal force coefficient $C_{Ty}$ with higher vane deflection angle is observed for both standalone propeller-vane system and the propeller-in-wing system. This increment in $C_{Ty}$ is approximately linear for both $90^\circ$-pitch PVW systems with respect to the vane deflection angle $\delta_V$, performance significantly improved in comparison to the SA PV system. Examining deflection-
specific trends, the $C_{Ty}$ curve slope reduces between $\delta_V = 20^\circ$ and $\delta_V = 30^\circ$ cases for the PV system, indicating possible vane stall. Additionally, the propeller placement in the integrated wing seems to have a relatively minor effect on the normal force coefficient.

Table 3. Effective Vane Deflection Derived from PV Orientation and Initial Vane Deflection Angles

<table>
<thead>
<tr>
<th>PV Orientation (Pitch, °)</th>
<th>Vane Deflection Angle ($\delta_V$, °)</th>
<th>Propeller Wake Deflection Angle ($\delta_{Ve}$, °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>75</td>
<td>-20</td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td>-10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>35</td>
</tr>
</tbody>
</table>

Considering the 75°-pitch PVW system for the same control metrics, a positive increment in $C_{Ty}$ is observed across vane deflection angles until an effective vane deflection angle of 35° where a reduction in $C_{Ty}$ appears due to vane stall. The normal thrust coefficient of the 75°-pitch PVW system shows improved thrust vectoring performance compared to the 90° orientation, thus building upon the success of the initial wing integration.

Figure 15b shows the resultant pitching moment coefficient $C_{Qx}$ across variable vane deflection angles for each static test case. A negative pitching moment coefficient indicates a stabilizing, pitch-down moment acting on the wing. An increment in the magnitude of $C_{Qx}$ occurs with each change of the vane deflection angle $\delta_V$. Again, the 90° PVW system has a positive effect on the generation of $C_{Qx}$ compared to the SA PV though the propeller location seems have a minor
effect on $C_{Qx}$. Both phenomena – incremental increases in magnitude of $C_{TY}$ and of negative $C_{Qx}$ – indicate a positive effect on thrust vectoring from the integration of a mock wing with the PV setup. For the 75°-pitch orientation of the PVW system, the pitching moment coefficient observes a small decrement in magnitude when compared to the SA PV case, which indicates decreased stability for the system, however slight.

Figure 15. a) Normal force coefficient and b) pitching moment coefficient of all experimental setups across vane deflection angles.

Axial thrust coefficient results across different vane deflection angles, which speak to the system’s vertical takeoff capability, are shown in Figure 16. Generally, the axial thrust force decreases with the increase of vane deflection angle $\delta_V$, as expected from typical thrust vectoring effects and system losses. For the 90° PVW setups, there is little difference between the $\delta_V = 0°$ and $\delta_V = 10°$ cases. Between $\delta_V = 20°$ and $\delta_V = 30°$, an average difference of 3.5% exists between the exposed and embedded propeller case, the former of which experiences greater axial thrust losses. Compared to the SA PV system results, the wing interference seems to have a negative effect on axial thrust generation with a 6% average loss of axial thrust observed across deflection angles. It is worth noting, however, that this decrease in axial thrust coefficient magnitude for the
integrated wing correlates to a stronger thrust vectoring performance. Examining the 75°-pitch orientation of the PVW system, the performance in axial thrust generation is similar to the 90° PVW system up to an effective deflection angle of 15° beyond which point the axial thrust coefficient of the pitched PVW better matches the SA PV system. Overall, the wing integration introduces a slightly negative effect on propeller axial thrust performance across deflection cases.

Figure 16. Axial thrust coefficient of all static experimental setups across vane deflection angles.

The efficacy of the propeller-vane system is determined by:

\[ \eta_8 = \eta_\theta \times \eta_T \]  

where:

\[ \eta_\theta = \tan^{-1}\left(\frac{T_Y}{T_Z}\right) \] and  
\[ \eta_T = \frac{\sqrt{C_{T_Y}^2 + C_{T_Z}^2}}{C_{T_Z \text{Bare Prop}}} \]

Equation 5 describes the exit vanes’ ability to deflect the propeller wake while maintaining the net thrust. Under ideal conditions, the direction of the deflected propeller wake is equal to the vane angle, indicating perfect thrust vectoring, while the total thrust of the PV setup is equal to that of a bare propeller operating at the same rotational speed and pitch. The individual components of the
static efficacy for each experimental design, $\eta_\theta \ast \eta_T$, are plotted together in Figure 17 below while Figure 18 shows the overall efficacies of the same iterations.

The overall wake momentum vectoring efficiency $\eta_\delta$ decreases with the incremental change in vane deflection angle $\delta_V$. For all PVW systems, the value of $\eta_\theta$ changes linearly with the increment of vane deflection angle $\delta_V$, extending from 0.9 at the lowest deflection to 0.8 at the highest. The value of $\eta_\theta$ decreases slightly when the propeller is set in the 75°-pitch orientation compared to the 90°-pitch case. Most noteworthy, however, is the value of $\eta_\theta$ for the SA PV case which falls most noticeably with the increase of $\delta_V$ from around 0.55 at 10° to 0.38 at 30°. The value of $\eta_T$ for all systems is similar between 10° and 20° deflections with a 10% decrement observed therebetween. Combining these initial components, the resultant $\eta_\delta$ for the standalone propeller-vane system appears significantly lower than those of all propeller-vane-in-wing systems as a result of very low $\eta_\theta$ conditions, the cause of which is readily observed in the normal force coefficient plot of Figure 15. Even at the highest vane deflection angle, all PVW systems far outperform the SA PV, maintaining about 80% efficacy with respect to thrust vectoring. This provides further confidence for not only the standard but also the pitched propeller performance with respect to the wing system, improving forward flight performance during transition while still generating enough vertical thrust for VTOL operations in hover.
Figure 17. Deflection and thrust efficacies, $\eta_\theta$ and $\eta_T$, with respect to vane deflection angle for all configurations under hover conditions.

Figure 18. The overall propeller-vane efficacy $\eta_\delta$ with respect to vane deflection angle for all configurations under hover conditions.
**Wind-On Testing Results**

The propeller rotational speed remained fixed at 100 RPS during wind-on experiments while the incoming freestream velocity was changed to obtain different advance ratio conditions. It is worth noting that the propeller disk was primarily oriented parallel to the freestream, resembling edgewise flight, but calculations for the advance ratio follow that of a conventional fixed wing configuration where the propeller plane is perpendicular to the freestream.

To effectively examine the performance effects of wing integration on the propeller, establishing an understanding of baseline cases is crucial for meaningful PVW system study: thus, the performance of a bare propeller and bare propeller integrated into a wing are shown. The range of the bare propeller pitch angles is set to match that of the effective vane wake deflection angles, $\delta_{ve}$. The normal and axial thrust coefficients for both baseline cases are shown in Figure 19 and Figure 20, respectively. It is clear that the normal thrust for the bare propeller increases with the increment of advance ratio for majority of the cases, however, when integrated the propeller into the shrouding wing, this trend is reversed with a clear decrement occurring for all $C_{TY}$ values at higher advance ratio. The massive flow separation occurring at the wing opening as well as the changes in the incoming freestream direction that the propeller encounters when integrated into the wing are likely the cause of such performance changes.
Figure 19. Normal thrust coefficient values across advance ratio conditions for a) a bare propeller and b) a bare propeller integrated in a mock wing pitched to facilitate the effective deflections noted.

For the axial thrust coefficient, both baseline cases show a similar trend, with a lower propeller wake deflection angle $\delta_{Ve}$ (corresponding to a higher propeller pitch angle) resulting in a greater $C_{Tz}$ value at higher advance ratio. This trend reverses when increasing $\delta_{Ve}$. It is noteworthy that the magnitude of normal thrust, and thus of $C_{Tz}$, increases with incremental changes in $\delta_{Ve}$. When integrating the propeller into a mock wing, variations in the axial thrust coefficient magnitude as a result of changes in pitch reduce significantly, indicating a slightly positive effect of the wing on the axial thrust generation at higher $\delta_{Ve}$ and a slightly negative effect at lower $\delta_{Ve}$. 
Figure 20. Axial thrust coefficient values across advance ratio conditions for a) a bare propeller and b) a bare propeller integrated in a mock wing pitched to facilitate the effective deflections noted.

Figure 21 below shows the normal force coefficient $C_{TY}$ at different vane deflections across a range of advance ratios from 0 to 0.7 for the 90°-pitch propeller-in-wing system. A positive coefficient represents forward-vectored thrust generated by deflection of the propeller wake, and a negative coefficient represents additional drag induced by the propeller-vane system stall and blockage. As advance ratio increases, a clear decrement of $C_{TY}$ is observed which agrees with the overall trend seen in Figure 19b. A consistent difference in thrust vectoring performance with respect to vane angle is observed across advance ratios with a higher deflection angle generating a more positive $C_{TY}$ value. For the 90°-pitch case, at $J < 0.3$, a positively directed normal force may be achieved with at the maximum value of $\delta_v = 30^\circ$. As this is within the bounds of operation for most fixed rotor aircraft, such a performance is accepted as realistic for the anticipated flight conditions of any applied operations.
Figure 21. Normal thrust coefficient across advance ratio conditions for different vane deflection angles for PVW at 90°-pitch orientation.

For the pitched PVW orientation results shown in Figure 22, trends observed in baseline and standard pitch orientations still persevere. A positively directed normal force may be achieved up to the maximum advance ratio tested, $J = 0.7$, using the highest vane deflection, $\delta_{Ve} = 35°$. It is worth note that the normal force measurement observed does not account for the drag on the wing airframe which the propeller-vane system needs to overcome to facilitate forward flight. Based on the wind tunnel experimental data collected in UD-LSWT on a sized-down Eppler 479 wing (effective aspect ratio of 4) under similar Reynolds number conditions, this airframe drag coefficient at low angle of attack will be approximately 0.03. For the wing airframe tested, the magnitude of vectored thrust created by the vanes in a 90°-pitch orientation may thus overcome the wing-based drag under $J < 0.16$ at a vane deflection angle of 30°, and the vectored thrust of the 75° orientation may overcome the same drag under $J < 0.22$ at an effective deflection angle of 35°.
Figure 22. Normal thrust coefficient across advance ratio conditions for different vane deflection angles for PVW at 75°-pitch orientation.

Drag is an important aspect to consider when determining the efficiency of the vane thrust vectoring system. There are several aspects of the PVW system which contribute to the overall drag coefficient thereof. The vane placement in the wing results in a bleeding through of air from the lower to upper wing surface, subsequently creating drag. The sharp corners at the edge of the wing housing near the vane system lead to flow separation, causing further increase in drag coefficient. Blockage from exposed exit vanes as well as propeller area itself increase the overall drag coefficient of the wing as well.

An additional, unexpected drag component appeared in the PVW system as a result of the propeller rotation, leading to significant differences in the drag force between the propeller-on and the propeller-off condition. The direct measurement of drag force ($-F_y$) from the PVW system at neutral vane deflection conditions ($\delta_v = 0^\circ$) for different advance ratios is shown in Figure 23. Here, an increment in the observed drag force corresponds to the incremental change in advance ratio for all cases, but the drag force experienced by the PVW with propeller-on condition is
significantly higher than that of propeller-off, even when comparing the sum of the bare propeller and PWV with propeller-off at $J < 0.52$. As such, the additional drag due to propeller spin is defined as its own distinct phenomena, a propeller-induced drag.

Figure 23. Drag force experienced by different configurations across variable advance ratio conditions: for PVW, $\delta_{\nu} = 0^\circ$ (embedded propeller).

Smoke flow visualization was performed on the $\delta_{\nu} = 0^\circ$ case at $J = 0.2$ to determine the differences between propeller-on and the propeller-off cases of the $90^\circ$-pitch PVW system. A smoke wand with a diameter of 12.7 mm was placed upstream of the wing in the tunnel flow. Side views of the PVW system under both conditions are shown in Figure 24; the smoke boundary is traced with the red dashed line in each view. In the propeller-on case, the flow near the lower surface of the wing is sucked into the wing opening from the lower surface to the upper and is subsequently directed downward once again by the propeller. When the propeller is off, the flow visualization shows a different flow behavior. The flow does not cross from the lower surface of the wing to the upper surface: instead, the flow continues downstream as it normally would across a conventional wing in flight. Deflection and bending of the freestream in the propeller-on condition is hypothesized to be the additional source of drag experienced by the PVW system. Hence, further development of the PVW system is essential to provide better forward flight.
performance for the PVW system in the future, preventing this unexpected flow bending in subsequent investigations.

Figure 24. Side and underside views of flow visualization of PVW system (embedded propeller) at $\delta_v = 0^\circ$ and $J = 0.2$.

Behavior of the pitching moment coefficient $C_{Qx}$ for dynamic testing of the propeller-in-wing system is shown below in Figure 25. A negative $C_{Qx}$ value indicates a pitch down moment and positive $C_{Qx}$ indicates an upward pitching moment. When $J < 0.15$, negative values of $C_{Qx}$ may be achieved for the 90°-pitch PVW orientation by adjusting the value of $\delta_V$ within the experimental bounds of 0- and 30-degree deflection. At $J > 0.15$, however, additional control surfaces or small balancing rotors would be required to provide longitudinal stability for this system. The propeller location appears have a minor effect on $C_{Qx}$ in this case.

For the 75° orientation of the PVW system shown in Figure 26, negative values of $C_{Qx}$ may be achieved by adjusting the value of $\delta_V$ within the experimental bounds of 0° and 20° deflection at $J < 0.15$. Despite the increased range of successful thrust vectoring for this PVW setup, the ability to provide longitudinal stability for the system is limited to the same range as the 90°-pitch case.
Figure 25. Propeller pitching moment coefficient across advance ratio conditions for different vane deflection angles for PVW at 90°-pitch orientation.

Figure 26. Propeller pitching moment coefficient across advance ratio conditions for different vane deflection angles for PVW at 75°-pitch orientation.
Figure 27 and Figure 28 below show the axial thrust generated by the 90°- and 75°-pitch PVW systems under dynamic test conditions. The propeller axial thrust coefficient $C_{Tz}$ increases with advance ratio in both cases, a trend which is also observed in Figure 20b. Though greater thrust is produced by the propeller-in-wing system at higher advance ratios, the design’s ability to vector thrust diminishes significantly due to the dominance of freestream dynamic pressure compared to that of the propeller wake. As high advance ratio conditions are not realistic for most UAV-type applications, this result does not condemn the system overall.

Higher vane deflection angle cases do consistently exhibit lower axial thrust coefficients, attributed at least in part to subsequently increased normal thrust values. In a notable exception, the performance of the $\delta_V = 0°$ and $\delta_V = 10°$ cases for the 90°-pitch orientation show little disparity in axial thrust despite noticeable changes in normal force. Examining propeller placement sensitivity, at $J < 0.3$, a 4% average difference is observed between the embedded and exposed propeller cases, the exposed showing the better performance in $C_{Tz}$.

![Figure 27. Axial thrust coefficient across advance ratio conditions for different vane deflection angles for PVW at 90°-pitch orientation.](image)
For the 75°-pitch orientation, lower average axial thrust coefficient values are observed across advance ratio conditions compared to the 90°-pitch case, keeping with the comparatively lower 75° bare propeller baseline. In general, higher deflection corresponds to greater losses in axial thrust; the performance of the $\delta_{ve} = 15^\circ$ case has the highest $C_{Tz}$ value as the actual vane deflection angle $\delta_v$ is equal to zero. Following are the $\delta_{ve} = 5^\circ$ and $\delta_{ve} = 25^\circ$ cases which include a small loss in $C_{Tz}$, and a more significant loss in $C_{Tz}$ appears for $\delta_{ve} = -5^\circ$ and $\delta_{ve} = 35^\circ$. Thus, an increase in vane deflection angle corresponds to less observed axial thrust.

When compared to the performance of the 90°-pitch orientation, at low advance ratio, the $\delta_{ve} = 5^\circ$ and $\delta_{ve} = -5^\circ$ cases of the pitched PV case, themselves similar to the $\delta_{ve} = 0^\circ$ case in Figure 27, have an average of loss of 4% in $C_{Tz}$. Recall that the 75°-pitch orientation has a much better performance with respect to normal thrust (Figure 21 and Figure 22). This indicates that with a small loss in the efficiency of the PVW system for vertical takeoff performance, the 75°-pitch orientation shows significant improvement in thrust generation during forward flight.

![Figure 28. Axial thrust coefficient across advance ratio conditions for different vane deflection angles for PVW at 75°-pitch orientation.](image-url)
The overall efficiency of the propeller vane system in forward flight is defined in equation 7. To reliably compare all combinations of propeller pitch and vane deflection, the system thrust efficacy $\eta_{TV}$ is calculated using a bare propeller baseline case corresponding to the same vane deflecting angle $\delta_{ve}$ as is applicable to each experimental test condition (see Table 3).

$$\eta_{TV} = \eta_{T\delta} \times \eta_p$$

(7)

where:

$$\eta_{T\delta} = \frac{C_T_{PVW}}{C_T_{Bare\ Prop}}$$

(8)

$$\eta_p = \frac{C_p_{Bare\ Prop}}{C_p_{PVW}}$$

(9)

The overall efficiency of a bare propeller set in the mock Eppler 479 wing, examined for force and torque results in Figures 19 and 20 above, appears in Figure 29 below, compared in practice to a standalone propeller. To understand the performance effects of the PV system alone, the influence of the integrated wing must be examined separately.

Figure 29. Overall thrust vectoring efficiency of a bare propeller in wing across advance ratio conditions for different effective deflections varied with propeller pitch.
It is clear that the overall $\eta_{TV}$ decreases with rising advance ratio, as expected based on momentum losses from the system. Considering propeller wake deflection, at a higher $\delta_{Ve}$, the effect of the wing integration on bare propeller performance during forward thrust generation diminishes. This provides a basic performance reference for the PVW system study.

Figure 30 shows the overall thrust vectoring efficiency for different effective wake deflections of the 90°- and 75°-pitch PVW systems. Experimental conditions leading to impractical system efficiencies where the value of $\eta_{TV}$ drops below zero are excluded.

In general, the overall efficiency decreases with increasing advance ratio in agreement with the trend shown in Figure 29. For both 90°-pitch cases, at an advance ratio lower than 0.25 the efficiency of the design eventually drops below zero, even for a 30° vane deflection angle. This once again reflects upon the practical advance-ratio-based operating range for the PVW system which agrees with the results depicted in Figure 22. Comparing the exposed and embedded propeller cases, the PVW system with propeller embedded has 3% higher overall thrust vectoring efficiency on average than that with the propeller exposed. It is worth noting, however, that the vertical thrust generated by the exposed propeller is around 2% higher than the embedded propeller (Figure 26). Thus, the embedded propeller placement within the PVW system will foster a better performance in forward flight while the exposed propeller PVW system will have a better performance in the transition flight.

For the 75°-pitch PVW case, the general trend seen for a 90° pitch perseveres. As the effective vane deflection angle increases, the practical advance ratio range of operation for the PVW system subsequently extends, reaching to $J = 0.7$ for the $\delta_{Ve} = 35°$ deflection case. This represents a significant improvement from the 90°-pitch orientation. In terms of efficiency, then, the 75°-pitch PVW system outperforms the 90°-pitch case.
Figure 30. Overall thrust vectoring efficiency of all PVW iterations across changing advance ratio conditions for different effective vane deflection cases.
Conclusions

The efficiency of a vane-based thrust vectoring design was determined for both a standalone propeller-vane (SA PV) system and a propeller-vane system embedded in a wing (PVW) through static and wind-on tests. The following are significant takeaways from experimental results and analysis:

- Static testing indicated that the integration of a wing had a positive effect on the propeller-vane system, providing higher thrust vectoring efficiency in hover.
- The 90°-pitch PVW system was capable of vectoring the propeller wake up to a 30° deflection while maintaining more than 80% of the overall thrust generated.
- Under transition and forward flight conditions, the 90°-pitch propeller-in-wing system was able to generate forward thrust within the practical forward flight speed range where J < 0.3. For the 75°-pitch PVW orientation, the same system successfully produced forward thrust for J < 0.7. Across iterations, the ability to provide longitudinal stability was limited within J < 0.15.
- Propeller location sensitivity analysis revealed that the exposed and embedded propeller test cases for the PVW system had similar performance, the exposed featuring a slightly lower thrust vectoring capability but a higher overall efficiency. The exposed propeller placement case for this system will thus outperform the embedded in hover and transitional flight conditions, but the embedded will perform best in forward flight.
- The 75°-pitch PVW tests observed a better overall thrust vectoring efficiency when compared to the 90°-pitch case, though the latter is still recommended for most practical applications.

To further develop this study, the geometry of the integrated wing’s leading-edge design should be adjusted, focusing on lip geometry to address duct-like performance effects. An
investigation into the limits of positive propeller pitch effects on the integrated propeller-vane (PV) system will expand upon the initial pitch sensitivity findings; within these bounds, a redesign of the PV system itself to reduce vane-freestream interaction (and thus flow bending and blockage, induced drag, and destabilizing pitching moments) is also recommended.
References


