Effect of Locational Optimization of Electronic Ducted Fan Propulsion Systems on the Aerodynamic Efficiency of a Wing

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Nomenclature

EDF	=	Electric Ducted Fan
L/D	=	Lift over Drag Ratio
AE	=	Aerodynamic Efficiency
L	=	Lift Force
D	=	Drag Force
TTU	=	Tennessee Technological University
6 DOF	=	6 Degrees of Freedom
DAQ	=	Data Acquisition Device
UAV	=	Unmanned Aerial Vehicle

Abstract

Distributed electric ducted fan (EDF) propulsion systems in aerospace applications have attracted significant interest as the industry begins the shift to electric propulsion technology. Electric propulsion provides many benefits over traditional fuel propulsion systems in many regards, not limited to the lightweight nature of the technology, simplification in complexity of the systems compared to traditional aviation fuel powered propulsion units, increased emissions regulations to reduce carbon footprint, reduced infrastructure and supply chain related expenses, quieter noise levels of aircraft, and easier modularity and integration capabilities of these electric systems. Considering the above factors, this work focuses on the optimal integration of such EDF housing on the wing, as location, grouping, and the number of these units influence the wing's aerodynamic efficiency (AE). The aerodynamic impact of EDF housing on a wing, specifically due to the increased turbulence (and therefore a combination of increased drag and degraded lift) from boundary layer and wake interaction of the flow around the wing, is therefore investigated through experimental methodology using a low-speed wind tunnel testing to develop an understanding and characterization of this interaction. The effects of these parameters on the aerodynamic efficiency (AE) of a wing will be experimentally determined through numerous tests to quantify the impact of adjusting them, leading to the best placement strategy for the successful implementation of EDF technology on new-age aircraft while retaining the highest possible performance. This work studies the effect of how these factors can lead to conclusions to experimental best placement strategies that ensure the minimum drag (D) penalty of a wing, and therefore an entire aircraft, as well as ensuring the maximum amount of lift (L) is retained, leading to the highest L/D, or aerodynamic efficiency (AE) possible. Using a low-speed subsonic wind tunnel at Tennessee Technological University (TTU), different EDF

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housing configurations are tested on a baseline wing, and the experimental results are directly compared to conclude the optimal location, grouping, and number of EDF motors. Testing will be conducted on 3D-printed housings capable of holding EDF propulsion units, and the results will be presented to showcase how varying the parameters in question affects the AE of the baseline wing. Analysis of the results reveals an optimal EDF positioning strategy and defines clear best-practice guidelines to minimize the drag (D) penalty on the wing.

I. Introduction

As the interest and need for efficient electric propulsion methods are growing due to the reasons listed previously, the prevalence of EDF motors becomes increasingly feasible and ideal for converting electrical power into thrust [1-3]. Compared to traditional propellers, EDF motors provide greater static thrust at the same power and fan diameter, as found by Moshier and Bulaga in their comparison of EDF motors and open propellers [4]. From the same source, and from the inherent design of the EDF's enclosed shroud, the blades are confined within a housing, offering greater safety during on-ground operations. As the EDF's shroud is fundamental in the design of directing the airflow through the blades, the unit is therefore inherently much easier to integrate into aircraft design on a large scale, as traditional turbofan engines already possess this same shrouded design. Integrating or retrofitting an existing aircraft EDF-style system is therefore much more feasible than adding a propeller, as similar geometry between EDF motors and existing propulsion systems is evident.

As EDF propulsion systems can come in many sizes and configurations, the case for multiple distributed units rather than a single large traditional propulsion engine is considered. As these units are relatively lightweight, their thrust density is much higher than that of traditional propulsion systems, allowing less structural consideration when mounting them along the wing. Traditionally, turbofan or turbojet engines are mounted under the wing and close to the fuselage, primarily because of their high weight. This engine position may not be aerodynamically optimized, as structural considerations may override the most efficient location when all factors are considered. EDF, with its lower weight, may allow pushing the propulsion units closer to the wing tip if testing shows the AE is higher at the tip than at the root. As aerodynamic and propulsion interaction is often difficult to model with CFD, as well as being computationally expensive and time-consuming, wind tunnel testing is an alternative that will allow direct comparison of many cases using the same experimental setup, changing the grouping, location, and amount of EDF units quickly with a modular 3D printed design [5]. Using such a setup with matched flow conditions across cases will ensure the highest accuracy in the values used to compare aerodynamic data, enabling a strong conclusion about optimized configurations. Using the low-speed wind tunnel on TTU's campus [5-8], the included load cell and manometer setup will allow the flow to be matched and the forces to be collected using an ATI Mini85 6 DOF load cell. Force data will be collected at 1000 Hz using a National Instruments DAQ and averaged over the collection period to obtain a single force set. The resulting L and D values are used to calculate the L/D for each configuration, yielding a nondimensional number suitable for comparison across cases.

II. Problem Statement

Drag (D) introduced by the housing systems for any propulsion method that is integrated onto the wing of an aircraft introduces turbulent flow due to the non-streamlined geometry that confines the engine and secures the structure to the wing, affecting the aerodynamic efficiency by decreasing L and increasing D. The amount of the wing that experiences this turbulent flow is proportional to the amount of AE that is lost when air passes over the wing and thus finding a configuration of such housings to minimize Drag (D) penalty due to this turbulent flow while retaining the most lift (L) is the focus of this study, as previously studied [5]. Understanding the relationships among spacing, grouping, and the positioning of the housings will inform more informed decisions on the best positioning strategy, and wind tunnel testing will be used to validate the best-performing cases experimentally.

As EDF terminology is used for this work, the findings can be applied to any system containing similar geometries and configurations. The use of the EDF motor housing design for the experiment provides the opportunity for future investigation using the same experimental setup. The findings of this work, as well as future investigations into dynamic thrust testing, will enable the successful integration of new propulsion systems onto small-scale UAVs and large-scale commercial aircraft, especially as new technologies may reduce limitations imposed by factors such as structure and weight associated with existing propulsion systems. The target of this work is to define the best strategy for the placement, grouping, and positioning of propulsion systems (using EDF-inspired geometry) on a wing, based on aerodynamic performance comparisons of wind-tunnel testing results across different configuration cases to determine the optimal configuration.

For this work, three characteristics of housing positioning will be experimentally validated:

1. Analyzing the effects of EDF placement in terms of number and location

More housing will introduce increased drag (D) on the total wing assembly; thus, understanding the relationship between the amount of housing and the drag (D) increase, and how it relates to AE, is fundamental. The possibility that a configuration with more strategically placed housing, having a higher AE than configurations with fewer housings, exists; exploring the number may yield a way to incorporate more units for the same or lower drag (D) penalty. Likewise, the location of the housing is understood to influence the AE of the entire assembly, and thus varying the housing location may yield a similar result, especially when combined with arrangements of different numbers.

2. Analyzing the effects of EDF placement in terms of grouping

The housing grouping strategy will be explored, as the drag (D) penalty may be influenced by unit spacing. If a relationship is found for inter-unit spacing, an optimal spacing strategy can be defined to converge on the best configuration, ranging from equally spaced along the entire wingspan to fully grouped arrangements in which all housings touch.

3. Understanding the effects of under-wing or top-wing placement

Because the relationship between AE dependence and whether the housings are placed on the top or bottom of the wing is unknown in this experimental setup, testing specific cases will show whether placing the arrangement on the top or bottom surface of the wing is more optimal in terms of performance.

III. Literature Review

Past investigations into the effect of electric distributed propulsion have concluded that the installation and associated geometry of the propulsors used have a considerable, measurable effect on aerodynamic performance. The NASA Langley Adaptable Distributed Electric Propulsion Testbed (ADEPT) project conducted an initial investigation into the effects of EDF units on a wing, focusing on angle-of-attack and fan-speed variations [9]. This research uses a symmetrical wing with varying numbers of EDF units, with units placed at the leading and trailing edges, behind the trailing edge, in front of the leading edge, and in both top- and bottom-mounted surface configurations. This testing involves both static and dynamic testing of the fans and shows the performance differences resulting from flow changes across the dependent variables outlined [10]. This work aims to expand the understanding of the effect of spanwise positioning of such EDFs on aerodynamic performance.

IV. Experimental Testing Approach

Determining the effect of housing location, grouping, and amount on the AE of a wing directly involves the introduction of turbulent flow from the non-uniform EDF housing and supporting structure. As the housing connection to the wing can vary greatly depending on the application used, this will not be included in the scope of this project. A simple housing for the EDF has been designed and will be used for all testing purposes. Only one size of EDF housing (designed for a 70 mm unit) will be tested, to avoid excessive complexity in the analysis. The only parameters that will be changed in this work are as follows:

1. Amount of EDF Units

Tests will be run with housing arrangements of 1 to 4 units per wing. Testing for each number of housing units will be compared between like-numbered cases. Between the identically numbered housing unit test cases, the optimal configuration will be determined.

2. EDF Spanwise Location

The housing will be positioned in groups at three locations along the wing: at the wing tip (0% of the total span), 25% of the total span, and the middle of the wing (50% of the total span). The wing has a rectangular planform, so extending the tests to encompass the full wing is not required, as this would introduce repeated, yet mirrored, cases. Configurations using 1 through 4 housings will be analyzed in this manner, totaling.

3. EDF Grouping

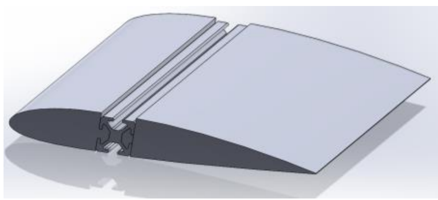
For the analysis of grouping the housings, otherwise classified as the spacing between the units, 3 cases will be analyzed: no spacing (otherwise known as grouped cases, discussed previously), equally distributed spacing across the wing from tip to tip, and a middle ground approach of equal spacing within an area of 25% of the chord to 75% of the chord. These last two cases will be run for configurations of 2 to 4 units, for a total of 6 cases.

4. Top or Bottom of Wing Placement

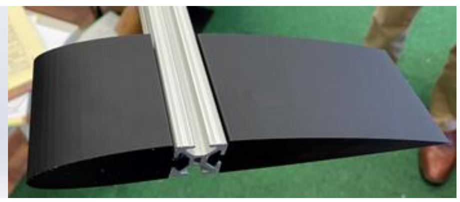
As the effect of the housing unit position on the top or bottom of the wing is unknown, testing of the wingtip location of 1 through 4 housings will be conducted on the upper and lower surfaces of the wing.

V. Experimental Setup

The EDF housings are 3D-printed and designed to hold a 70 mm EDF unit around the circumference of the casing. Below the housing is a slotted attachment that slides into an extruded aluminum bar, allowing infinite adjustment of each motor's position. The NACA 4412 wing leading and trailing edges are similarly 3D-printed and slot into the extruded aluminum to create the wing, as shown in the prototype design in the images below. The wing has a span of 1 m and a chord of 200 mm, with an aspect ratio of 5.



(a)

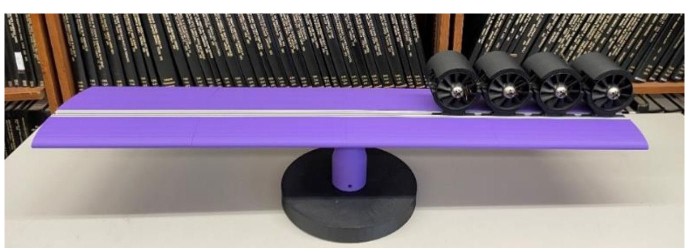


(b)

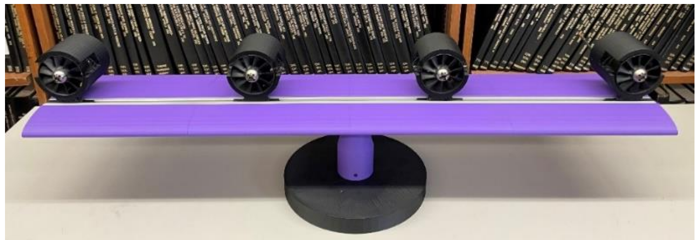
(c)

Figure 1. (a) CAD model, (b) 3D printed airfoil with a rail, and (c) wing and EDF housing experimental setup prototype

The full wing is pictured below, with an example experimental configuration of EDF housings and the motors included for clarity, although they were not present during testing. Figure 1(a) shows the 3D model of the wing that is compatible with the extruded aluminum bar, while Figures 1(b) and 1(c) show a test fit of the wing design as well as a preliminary housing design for testing the tolerances of the extruded aluminum interior profile. The extruded aluminum bar runs the entire length of the wingspan, enabling it to be used in any housing location or configuration. The slot on the bar is taped over during testing, providing a smooth surface that closely matches the original airfoil profile and mitigates any significant penalty to aerodynamic performance. Figure 2(a) and 2(b) show example experimental testing configurations of EDF units in the designed housings to demonstrate the utility and application to current and future testing.



(a)



(b)

Figure 2. (a) Wing and EDF experimental setup with 4-unit groups at the tip location, and (b) equally spaced 4-unit configuration

Wind tunnel testing will be conducted for each configuration at three different tunnel velocities to ensure that flow speed-dependent effects are captured. The wind tunnel is controlled by fan rotation speed (Hz), so the flow is measured with a manometer to match the velocity for each case. Figure 3(a) represents the baseline case of the wing that will be used, mounted in the wind tunnel. Figures 3(b), 3(c), and 3(d) demonstrate a select few cases of the total testing set. Figure 3(b) consists of the 4 housing configurations with equal spacing across the entire wingspan, Figure 3(c) consists of the 4 housing configurations grouped at the wing tip, and Figure 3(d) consists of the 3-housing configurations grouped at the wing tip that are mounted to the bottom surface of the wing.

(a)

(a) **(c)** **(d)**

Figure 3. (a) Equally spaced, (b) grouped, and (c) baseline wing and EDF housing units at the bottom of the wing

VI. Wind Tunnel at TTU

The Wind Tunnel facility at TTU, shown in Fig. 2, comprises one subsonic, open-loop Wind Tunnel that utilizes a 125-horsepower (93 kW) motor with variable-pitch blades. This Wind Tunnel features a 3-meter-long test section with a 1.25-meter-wide by 1.25-meter-tall cross-section. The tunnel can accommodate a flow of up to 20 m/s (70 mph) at approximately 38 m^3/s (80,000 CFM) through a variable-frequency controller. Force measurements are taken by an ATI Mini85 Load Cell placed on the bottom surface of the Tunnel's test section.

Figure 4. TTU Wind Tunnel

(a) **(b)** **(c)**

Figure 5. (a) traverse system, (b) load cell boom arm, and (c) full view of test section

The load cell, as shown in the figure above, can measure forces and torques in all primary axes (FX, FY, FZ, TX, TY, TZ). This is run in parallel with LabVIEW using a DAQ (data acquisition) device, supporting a sampling rate of up to 1000 Hz. The Wind Tunnel also features a three-directional traverse system, as shown above, for instrument integration to map the flow turbulence within the Tunnel. The traverse system can travel 1 meter in the x, y, and z directions. The practical test volume is 1 meter by 1 meter, accommodating the traverse system's full reach. The traverse system accommodates a hotwire anemometer probe and various 1-D and 2-D probes.

VII. Experimental Procedure

For all different configurations, the table below outlines the configurations to be tested:

Number of EDFs	1	2	3	4
Spanwise Locations for Grouped Housings	0%, 25%, 50% [Figure 6(a) – 6(c)]	0%, 25%, 50% [Figure 6(d) – 6(f)]	0%, 25%, 50% [Figure 6(g) – 6(i)]	0%, 25%, 50% [Figure 6(j) – 6(l)]
Spacing for Equally Distributed Cases	N/A	0% to 100% of span [Figure 6(m)]	0% to 100% of span [Figure 6(o)]	0% to 100% of span [Figure 6(q)]
		25% to 75% of the span [Figure 6(n)]	25% to 75% of the span [Figure 6(p)]	25% to 75% of the span [Figure 6(r)]
Top/Bottom Placement	Housing at the tip [Figure 6(s)]	Housing grouped at the tip [Figure 6(t)]	Housing grouped at the tip [Figure 6(u)]	Housing grouped at the tip [Figure 6(v)]

Table 1. Housing Position, Grouping, and Spacing Testing Cases

For “grouped” housing arrangements, this is defined as when all housing units in a group are placed with no space between the units. When an EDF group is placed at a specific spanwise location, the middle of the housing group will be aligned with the particular location. For example, a group of four units at 50% would have two units on either side of the wing's mid-span. In equally spaced arrangements, the housing is distributed evenly across the spanwise area. Figures 6 (a) through 6 (v) showcase all of the experimentally tested configurations, also noted in the above table.

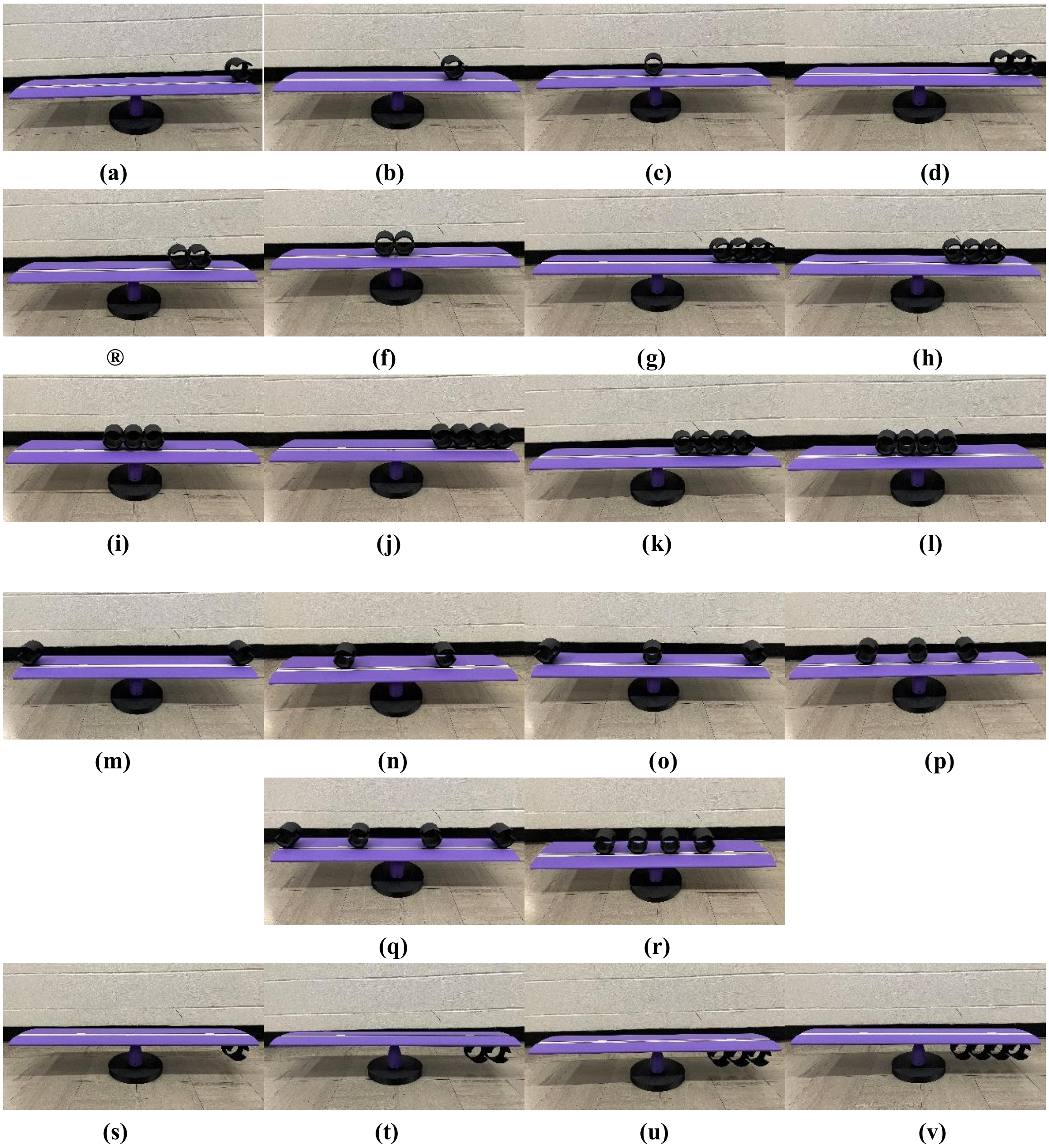


Figure 6. Pictures of all Experimentally Tested Housing Configurations

VIII. Result

For the cases outlined in the approach, the tunnel was run at 40 Hz for each case, and force data were collected for 10 seconds. No difference in pressure data was observed for the tunnel flow speed; the velocity was matched for each case to allow direct comparison. The data were averaged over the collection period to obtain the aerodynamic forces for each case. The plots below show the results of comparing AE for different EDF housing configurations.

The force data for the mounting hardware is taken at the same speed and subtracted from each result, giving only the L and D of the wing and EDF housings. L/D ratios are computed for each configuration and plotted with the corresponding configurations, resulting in the following figures. Figure 7 shows the aerodynamic performance of all 1 EDF housing unit configurations, while Figures 8 through 10 show the aerodynamic performance of 2 through 4 EDF housing unit configurations, respectively.

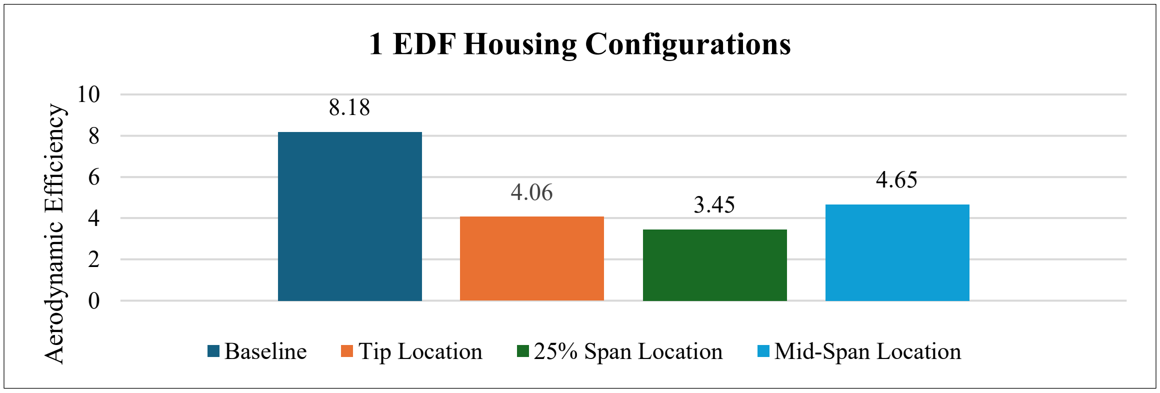


Figure 7. Aerodynamic Efficiencies of 1 EDF Housing Configurations

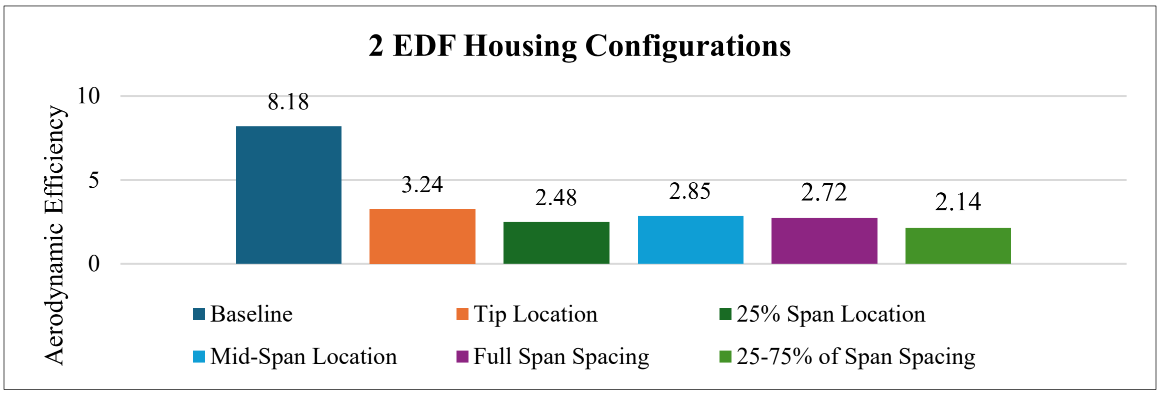


Figure 8. Aerodynamic Efficiencies of 2 EDF Housing Configurations

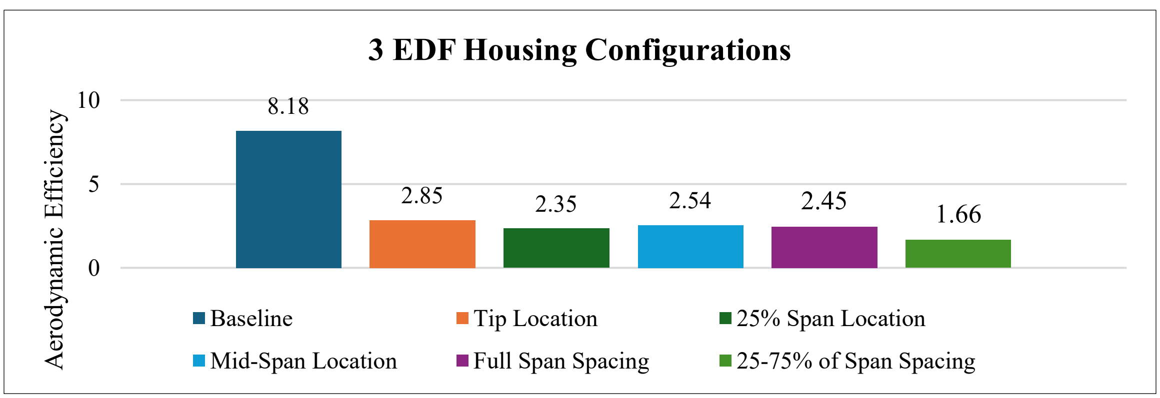


Figure 9. Aerodynamic Efficiencies of 3 EDF Housing Configurations

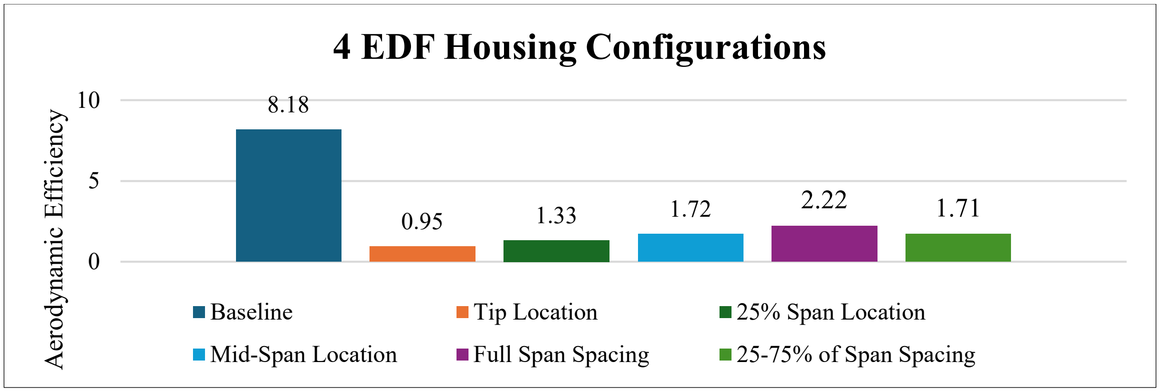


Figure 10. Aerodynamic Efficiencies of 4 EDF Housing Configurations

Generally, for grouped configurations, the lowest performance occurs when the groups are positioned at the 25% span location, except for the 4-housing configuration, as seen in Figures 7 through 10. When 4 housings are present, there is little difference in the positions of these groups, as the areas they occupy overlap across cases. For housings 1 through 3, the tip and mid-span locations perform best, with the tip locations trending toward better performance as more units are added. It has been shown that, for cases with 2 and 3 housings, the distributed cases perform the worst, as a larger portion of the wing experiences disrupted flow. For cases with 4 housing, however, the large area of grouped configurations introduces a much larger drag (D) penalty than equally spaced configurations. This may be due to housing in equally spaced configurations, which allows a relatively smoother flow across the entire wing compared to a concentrated area of heavily disrupted flow. Generally, the experimental results show that a grouped and tip-based locational strategy is optimal for reducing the drag (D) penalty on a wing for 2 and 3 housings, with a slightly less desirable, but still comparable, result for the 1-housing case compared to the mid-span location.

For analysis of the best strategy for mounting housing on the top or bottom surface of the wing, the results are shown below for cases with 1 to 4 housings.

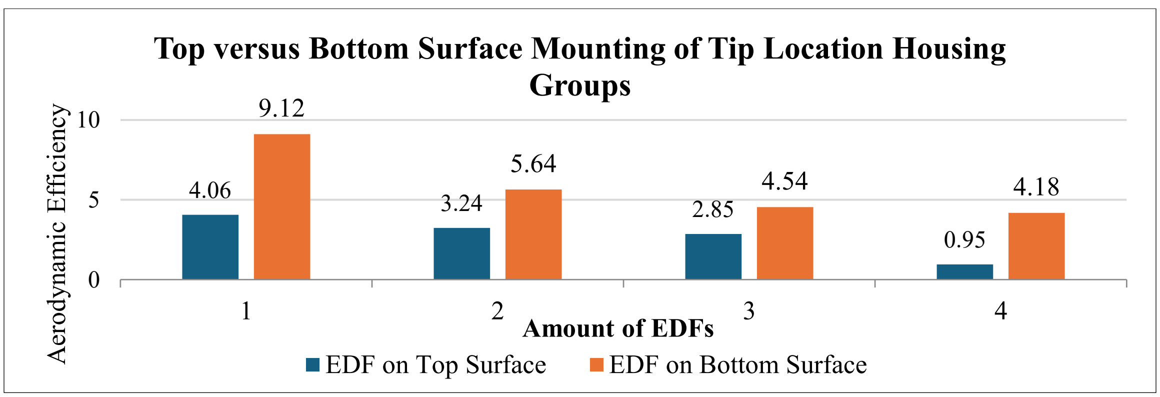


Figure 11. Aerodynamic Efficiency of Top versus Bottom-Mounted EDF Housings

From Figure 11, mounting the same grouped configuration at the wingtip on both the top- and bottom-mounted surfaces significantly affects aerodynamic efficiency. Mounting the housing at the bottom of the wing results in drastically higher AE across all cases; it is recommended that any successful implementation of EDF or other propulsion methods follow this result.

IX. Summary

Through this work, the authors have outlined the difference in AE that can be observed simply by changing the housing grouping strategy and mounting location. Through wind-tunnel testing of an experimental setup, the best-performing configurations from a predefined testing set have been determined, and the comparison of the same-numbered housing cases is presented. Grouping strategy, compared with inter-unit spacing strategies, has been shown to result in the highest AE cases for 1 through 4 housing configurations. Cases involving the top and bottom surface-mounted positions of the housing have been performed, with one case for 1 through 4 housings that determined bottom surface-mounted cases perform better overall. Results from all cases will lead to determinations of the best aerodynamic performance of propulsion configurations based on turbulence generation, demonstrating applicability to propulsion integration in future aircraft design. Table 2 shows the percentage differences for all cases with like-numbered housing units, and the percentage decrease relative to the highest AE for each case, noted in bold.

Number of Housings	Grouped @ Tip	Grouped 25% Span	Grouped @ Mid Span	Full Span Spacing	25%-75% Span Spacing
1	4.06 (-13.5%)	3.45 (-29.6%)	**4.65**	-	-
2	**3.24**	2.48 (-26.6%)	2.85 (-12.8%)	2.72 (-17.4%)	2.14 (-40.9%)
3	**2.85**	2.35 (-19.2%)	2.54 (-11.5%)	2.45 (-15.1%)	1.66 (-52.8%)
4	0.95 (-80.1%)	1.33 (-50.1%)	1.72 (-25.3%)	**2.22**	1.71 (-25.9%)

Table 2. Aerodynamic Efficiency of All Cases with Percentage Decreases

Table 3 compares the top- and bottom-mounted grouped tip location configurations for 1 through 4 housings, showing the percent increase for bottom-mounted configurations.

Number of Housings	Top-Mounted AE	Bottom-Mounted AE	Percent Increase in AE
1	4.06	9.12	76.8%
2	3.24	5.64	54.1%
3	2.85	4.54	45.7%
4	0.95	4.18	125.9%

Table 3. Aerodynamic Efficiency of Top- and Bottom-Mounted Grouped Tip Location Housing Configurations and Percentage Increase

X. Conclusion

The shift to distributed electric propulsion is rapidly approaching, opening new possibilities for aero-propulsion interaction investigations to determine optimal configurations when constraints tied to traditional propulsion are removed. If aircraft design shifts from a traditional one-engine-per-wing setup to a multi-unit EDF arrangement, the constraints of weight, size, and other factors may be removed entirely, allowing for an infinite expansion of location and grouping combinations. Studying the optimal configurations of such innovative systems to determine how best to achieve them is of critical importance in the early stages of this transition; thus, this work is an introductory exploration of the potential benefits of these systems. Today, the aerospace sector is concerned with many factors related to traditional propulsion methods, which are often powered by common hydrocarbon fuels. Reducing these emissions, developing quieter propulsion solutions, and lowering operational costs are key issues in the sector. The methodology outlined in this work may provide a path to a clean, quiet, and efficient electric propulsion strategy that would benefit the aerospace sector in its transition to this proposed technology.

Future testing will allow many configurations to be tested, allowing more definitive conclusions about the effect on a wing's AE based on the amount, grouping, location, and top or bottom-mounted position of the housings, allowing for an optimized placement strategy to be defined based on the lowest drag (D) penalty compared to the baseline wing. Future testing will include the previously discussed configurations, as well as any additional cases if trends are seen for a particular strategy. Furthermore, chordwise placement and height of the EDF will be considered, as these are also theorized to have a considerable effect. Dynamic testing is also of great importance, and this work outlines a starting point for investigating the induced flow around active EDF units.

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