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Comparative Analysis of Electroaerodynamic Propulsion and Electric Motors for the Zephyr 8 UAV

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Abstract

Electroaerodynamic propulsion is a thrust-generation technology that has gained significant attention in recent years. This study explains the advantages, disadvantages, and challenges of developing this propulsion system. Additionally, it compares the performance of electroaerodynamic propulsion with an electric propulsion system for the Zephyr 8 UAV. A mathematical model for the electric motor is presented, and performance charts are generated using data from the Zephyr 8 aircraft. Subsequently, a mathematical model for the electroaerodynamic propulsion system is developed. Using a hybrid GA-SQP optimization algorithm, an optimized design for the electroaerodynamic motor is created to achieve thrust comparable to the electric motor at an altitude of 21,000 meters and a flight speed of 10 m/s. Performance charts for the electroaerodynamic motor are also generated and analyzed. A comparison of the two systems indicates that aerodynamic ion propulsion could serve as a viable alternative to electric motors for the Zephyr 8 UAV, offering potential benefits in energy efficiency and high-altitude performance.

Keywords: Comparative Analysis; Electroaerodynamic propulsion; Electric propulsion; Optimization; Zephyr 8

1. Introduction

Electroaerodynamic (EAD) propulsion, also known as ionic propulsion, is an innovative technology that generates thrust and motion through electric forces instead of relying on mechanical moving components such as propellers or turbines. This technology operates based on the physical principles of electric fields and ion currents.

Electroaerodynamic propulsion utilizes air ionization and the generation of ionic currents. In this process, as illustrated in Figure 1, positive and negative electrodes are positioned at two separate points. When a high voltage is applied between these electrodes, the air in the vicinity of the positive electrode (the emitter) becomes ionized, producing positive ions. These ions are then accelerated toward the negative electrode (the collector). Along their path, the ions collide with air molecules, ionizing them as well.

The cumulative effect of these collisions and the acceleration of the ions results in the generation of a force known as ionic wind, which induces air movement and, consequently, produces thrust [1].

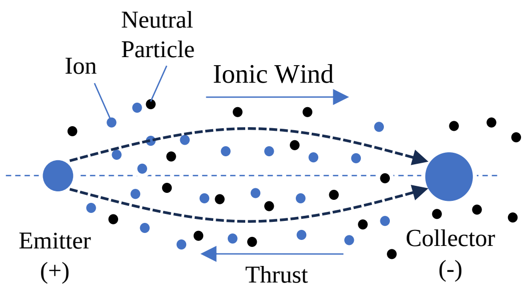

Figure 1. Schematic illustration of ionic wind generation in an electroaerodynamic propulsion system.

The electroaerodynamic (EAD) propulsion system offers several unique and distinct advantages, some of which are outlined below:

Silent Operation:
One of the most significant advantages of this technology is its silent or ultra-low-noise performance compared to conventional jet engines or propeller-driven systems. This feature enables a wide range of potential applications, particularly in areas such as urban air mobility and surveillance drones.

Absence of Moving Parts:

The lack of mechanical moving components reduces wear and failure rates, lowers maintenance requirements, and extends the overall service life of the system.

Potential for Higher Efficiency:
By eliminating mechanical components, the system can be further optimized for improved efficiency.

Thrust Generation in Rarefied Atmospheres and High Altitudes:
In low-density atmospheric conditions and at high altitudes, where the concentration of gas molecules is reduced, conventional propulsion systems — such as jet engines, which rely on fuel combustion and atmospheric oxygen — typically suffer from decreased performance. However, ionic propulsion systems are not subject to these limitations, as they utilize surrounding gas molecules (even at low densities) for ion production and do not require direct combustion. This characteristic enables ionic propulsion systems to operate effectively in highly rarefied environments, such as near the edge of Earth's atmosphere or in suitable near-space conditions.
Despite these advantages, electroaerodynamic propulsion systems also face certain limitations and challenges, which are described below:
High Electrical Power Requirements:
To produce sufficient ionic current, these propulsion systems require high voltage (typically in the kilovolt range), which leads to significant energy consumption.
Efficiency Challenges:
Although the systems operate silently and without moving parts, their overall efficiency is generally lower than that of combustion engines or propeller-driven systems in most practical applications.
Operational Environment Constraints:
Since these systems rely on ionizing air to function, they are not operational in vacuum conditions (e.g., outer space). As a result, their application is limited to atmospheric environments.
Electromagnetic Interference (EMI):
The high-voltage electric fields generated by the system may cause unintended interference with nearby electronic equipment.
According to the body of research conducted to date, most studies have focused on addressing the existing challenges of electroaerodynamic propulsion systems and improving their performance to enable them to compete with alternative propulsion technologies.
In this study, the characteristics of the Zephyr 8 motor were first extracted, and then the performance of the Zephyr 8 aircraft's motor was analyzed. Subsequently, a model of the electroaerodynamic propulsion system was developed, and using this model alongside a GA-SQP algorithm, an optimized propulsion system — equivalent in class to the Zephyr 8 aircraft motor — was designed. Finally, the obtained data were analyzed and evaluated.

2. Electric Motor Model of the Zephyr 8 UAV

Figure 2 shows a schematic diagram of the Zephyr 8 unmanned aerial vehicle. Additionally, some specifications of this aircraft are provided in Table 1 [2], [3].

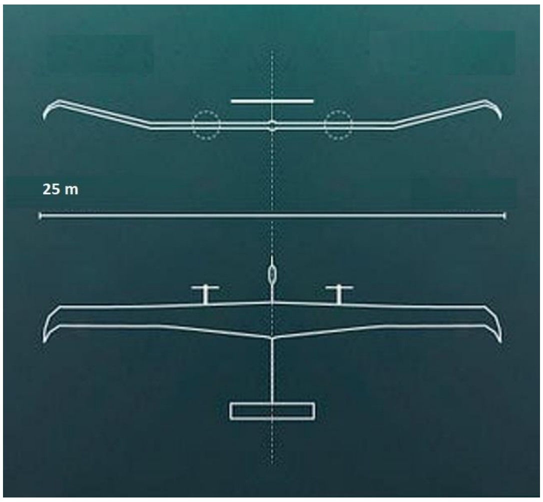

Figure 2. Schematic diagram of the Zephyr 8 unmanned aerial vehicle (UAV)

Table 1. Performance characteristics of the Zephyr 8 UAV

Parameter	Value
Cruise Altitude	21000 (m)
Flight Endurance	64 (days)
Range	56000 (km)
Mass + Payload	62 + 5 (kg)
Wing Span	25 (m)
Mean Wing Width	1 (m)
Tail Length	4.5 (m)
Tail Width	0.75 (m)
Propeller Diameter	1.25 (m)
Solar Panel Type	GaAs
Solar Panel Power Density	350 (W/m^2)

Based on the provided data, the specifications of the Zephyr 8 aircraft motor are presented in Table 2.

Table 2. Specifications of the Zephyr 8 electric motor

Parameter	Value
Maximum Thrust	7.094 (N)
Maximum Power Consumption	2482.812 (W)
Propeller Diameter	1.25 (m)
Mass	1.5 (kg)

3. Electroaerodynamic Propulsion System Model

Based on the equations derived from references [4] and [5], this system has four input variables, including the geometric dimensions (length, width, and height) and the applied voltage across the electrodes. The output variables are the system's mass, generated thrust, and power consumption.
Considering a scenario where the thrust produced by the system is matched to that of the Zephyr 8 motor at an altitude of 21,000 meters and a flight speed of 10 meters per second, and aiming to maximize both the thrust-to-mass ratio and the thrust-to-power-consumption ratio equally, the optimization problem can be formulated as expressed in Equation (1).

$$\begin{aligned}&\text{Maximize } f\left(\frac{T}{m},\frac{T}{P}\right)\\&\text{w.r.t} \rightarrow \ a,b,c,V \qquad (1)\\&\text{s.t } \rightarrow T = T_{Zephyr8}\ @\ 21000m, 10\ {}^{m}\!/_{s}\end{aligned}$$

To optimize this problem, the GA-SQP algorithm has been used. The GA-SQP algorithm is a combination of the Genetic Algorithm (GA) and Sequential Quadratic Programming (SQP), which is employed to solve complex nonlinear optimization problems. This algorithm benefits from the advantages of both methods to achieve optimal and efficient solutions.
The overall process works as follows:
GA is used for the initial search within the solution space to identify suitable regions for optimization.
Once suitable regions are identified, SQP is applied for a more precise search and to improve the obtained solutions.
After completing the optimization process, the main parameters of the propulsion system are presented in Table 3.

Table 3. Characteristics of the EAD Engine

Parameter	Value
Maximum Thrust	9.823 (N)
Maximum Power Consumption	1674.392 (W)
Dimension	0.160 × 0.253 × 0.113 (m)
Inlet Area	0.0286 (m^2)
Mass	1.410 (kg)

To compare the performance of the two propulsion systems, the results from propulsion systems were analyzed at altitudes of 0 m and 21,000 m, with each graph examined separately.

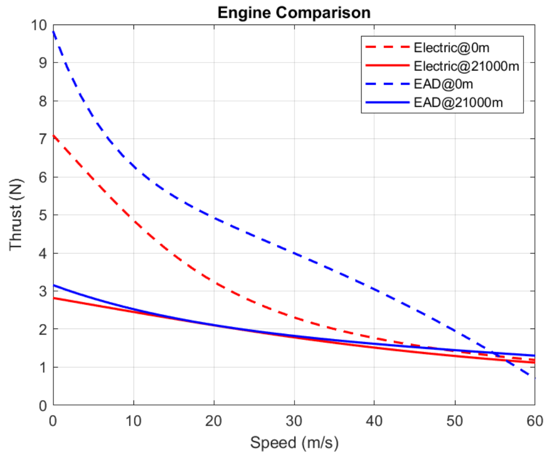

Figure 3 – Thrust vs. Velocity for Both Propulsion Systems

As shown in Figure 3, the thrust produced by both systems is nearly identical at an altitude of 21,000 m. However, at sea level (0 m), the electroaerodynamic (EAD) propulsion system outperforms the electric motor.

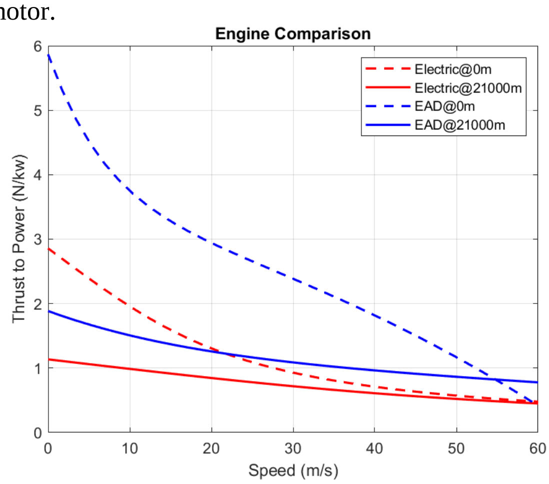

Figure 4 – Thrust-to-Power Ratio vs. Velocity for Both Propulsion Systems

Figure 4 demonstrates that due to the lower power consumption of the EAD propulsion system compared to the electric motor, the thrust-to-power ratio of the EAD system is significantly higher at both altitudes.

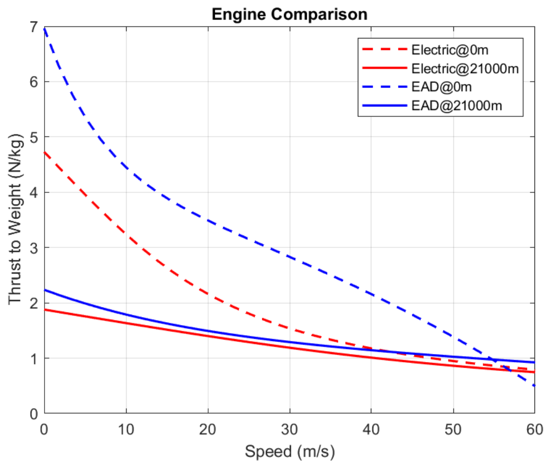

Figure 5 – Thrust-to-Weight Ratio vs. Velocity for Both Propulsion Systems

Given the similar weight of the two propulsion systems, their thrust-to-weight ratios at 21,000 m are very close. As seen in Figure 5, the difference in this ratio follows a trend similar to that in Figure 3.

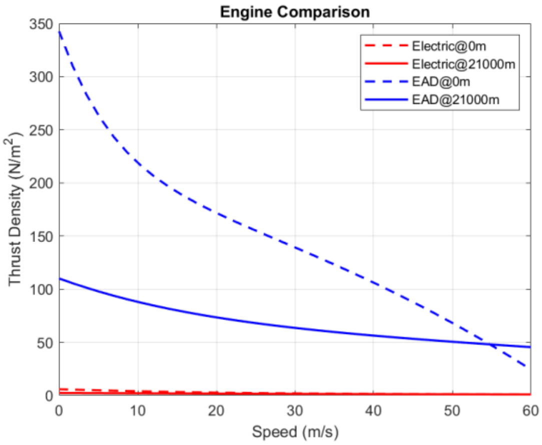

Figure 6 – Thrust Density vs. Velocity for Both Propulsion Systems

Figure 6 reveals that due to the smaller inlet cross-section of the EAD propulsion system and the long propeller of the electric motor, the thrust density of the EAD system is significantly higher than that of the electric motor.

4. Conclusion

In this study, the working principles of the electroaerodynamic (EAD) propulsion system were first introduced, followed by a discussion of its advantages and challenges. A review of recent research on overcoming these challenges and improving system performance was also conducted.

A mathematical model for the electric motor was developed, and performance graphs were plotted using data extracted from the Zephyr 8 aircraft. Subsequently, the EAD propulsion model was introduced, and an optimized EAD motor was designed using the GA-SQP optimization algorithm to match the thrust of the electric motor at an altitude of 21,000 m and a speed of 10 m/s. Performance graphs for the EAD motor were then generated.

Based on the comparative analysis, the following conclusions can be drawn:

The EAD motor exhibits a greater efficiency drop with increasing altitude compared to the electric motor. To achieve equal thrust at high altitudes, the EAD system requires higher thrust generation capability than the electric motor.

The designed ionic motor consumes less power than the electric motor, making it compatible with the power system of the Zephyr 8 UAV and enabling sustained flight.

Due to the similar mass of the two propulsion systems, their thrust-to-weight ratios are also comparable.

As mentioned in the introduction, the absence of moving parts in the EAD motor results in a longer lifespan compared to the electric motor, making it more suitable for long-endurance missions such as those of the Zephyr 8.

Given these results, the EAD propulsion system can be considered a viable alternative to the electric motor in the Zephyr 8 or other high-altitude UAVs.

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