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Addressing Fundamental Limitations in Electric Aircraft Propulsion Systems

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Abstract

The transition to electric propulsion in aviation promises lower emissions and reduced operational costs but faces significant technological challenges. This paper presents a comprehensive review of the current limitations and future prospects of electric aircraft by analysing performance trade-offs, powerplant integration, and aerodynamic efficiency across fixed-wing and VTOL designs. A key limitation is the low gravimetric and volumetric energy density of existing battery technologies, such as lithium-ion, which results in high powerplant weight fractions that restrict endurance, range, and payload capacity. However, trends indicate that larger electric aircraft may benefit from better scaling of powerplant mass and higher Reynolds number operation, improving aerodynamic efficiency. Another critical issue is the motor and propeller RPM mismatch causing efficiency losses, with the study exploring mitigation strategies like leading-edge upper-surface blowing to optimise lift distribution on high-RPM propellers. A parametric model is introduced for optimised blade design under electric propulsion constraints, concluding with an outlook on emerging battery technologies and propulsion airframe integration vital for the future of electric commercial aviation.

1. Introduction

The demand for pure electric aircraft is rapidly growing as the aviation industry intensifies efforts to meet ambitious environmental targets such as the FlyZero programme,[1] which aims to develop zero-emission commercial aircraft. Electric propulsion systems offer several compelling advantages over conventional thermal engines, including a simplified powertrain architecture, reduced mechanical complexity, and a superior power-to-weight ratio. These benefits have driven significant research and development in electric aviation, particularly for small and regional aircraft. However, the realisation of fully electric commercial jetliners remains constrained by several formidable challenges, prompting larger aircraft designs to prioritise hybrid-electric propulsion as an interim solution.

Foremost among these challenges is the fundamental limitation posed by current battery technologies. Despite continuous improvements, the gravimetric and volumetric energy densities of batteriesâprimarily lithium-ion chemistriesâremain orders of magnitude lower than conventional hydrocarbon fuels.[2] This disparity results in disproportionately heavy powerplant systems that limit aircraft endurance, range, and payload capacity, thereby restricting the viability of all-electric large commercial aircraft in the near to medium term.

Another critical constraint concerns efficiency losses within the motor-propeller system. Although high-power electric motors can achieve impressive peak efficiencies around 94%, the overall efficiency combining motor and propeller performance can fall to approximately 75%.[3] This drop is largely attributable to the mismatch between the high rotational speeds at which electric motors operate typically between 10,000 and 20,000 RPM, and the much lower optimal propeller speeds, which are generally below 4,000 RPM. This mismatch not only reduces system efficiency but also complicates propulsion integration and noise management.

This paper presents a thorough analysis of existing propeller design strategies[4,5] aimed at addressing these challenges. Building upon this review, a novel approach is proposed that leverages Blade Element Theory to mitigate the adverse effects of RPM mismatch. A key insight is that compressibility effects, which traditionally limit propeller performance at high tip speeds due to shock formation, may be alleviated by employing more aggressive sweep angles on

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the blade leading edges than those used in conventional designs. This innovative design perspective has the potential to unlock higher propeller tip speeds without incurring severe aerodynamic penalties.

The research described herein is ongoing, with anticipated advancements in propeller blade optimisation and motor-propeller integration expected to enhance overall propulsion efficiency significantly. Further results and conclusions will be incorporated prior to final submission, contributing to the advancement of electric propulsion technologies essential for the future of sustainable commercial aviation.

2. Electric Energy Density Limitation

Figure 1 presents a comparison of gravimetric and volumetric energy densities for various fuels and battery technologies relevant to aviation. Hydrogen fuel cells offer the highest gravimetric energy density among the options considered; however, their volumetric energy density is more than four times lower than that of conventional hydrocarbon fuels such as kerosene and gasoline. This low volumetric density introduces significant design and performance challengesâfor example, the need for a bulkier fuselage to accommodate high-pressure hydrogen tanks, which in turn increases profile drag and affects overall aerodynamic efficiency.[6]

In contrast, the most widely used lithium-ion batteries provide both gravimetric and volumetric energy densities below 1 MJ/kg and 1 MJ/L, respectively. While this severely limits the range and payload capacity of battery-electric aircraft, emerging battery chemistries under development show promise, with projected energy densities in the range of 2 to 3 MJ/kg.

The inherent energy deficiency of current battery technologies significantly impacts the powerplant weight fraction in electric aircraft, as illustrated in Figure 2. For mid-scale electric aircraftâtypically in the two- to seven-seat classâsuch as the Lilium Jet and Harbour Air eBeaver, the powerplant (including batteries, electric motors, and associated systems) can constitute up to 40% of the maximum takeoff mass (MTOM). This elevated fraction reflects the low gravimetric energy density of batteries, which necessitates a larger mass to store sufficient energy for even modest ranges.

In contrast, similarly sized conventional aircraft powered by internal combustion enginesâsuch as the Cessna 172 or the DHC-2 Beaverâachieve comparable range and payload performance with a powerplant weight fraction of approximately 12 to 15%, due to the superior energy density of aviation gasoline or kerosene and the lighter engine systems.

For larger transport-class aircraft like the Airbus A320neo, the powerplant weight fraction further decreases to around 6% of MTOM, as the scaling advantages of turbine engines and efficient airframe integration reduce the relative mass of propulsion components. This trend highlights a fundamental design constraint for electric propulsion in scaling up to larger aircraft categories without breakthroughs in energy storage technologies.

2.1 The Effect on Performance

The low gravimetric energy density of batteries has a direct and significant impact on the performance of electric aircraft, particularly in terms of endurance, range, cruise speed, and payload capacity. These limitations stem from the energy storage constraints imposed by current battery technologies. The standard endurance and range equations for electric and conventionally fuelled aircraft are provided below to illustrate these differences.

Electric Aircraft:

$$R = \frac{\eta \cdot E_b}{W} \cdot \frac{L}{D} \tag{1}$$

$$E = \frac{\eta \cdot E_b}{P_{\text{req}}} \tag{2}$$

Conventional Aircraft:

$$R = \frac{V}{c} \cdot \frac{L}{D} \cdot \ln\left(\frac{W_i}{W_f}\right) \tag{3}$$

$$E = \frac{1}{c} \cdot \frac{L}{D} \cdot \ln\left(\frac{W_i}{W_f}\right) \tag{4}$$

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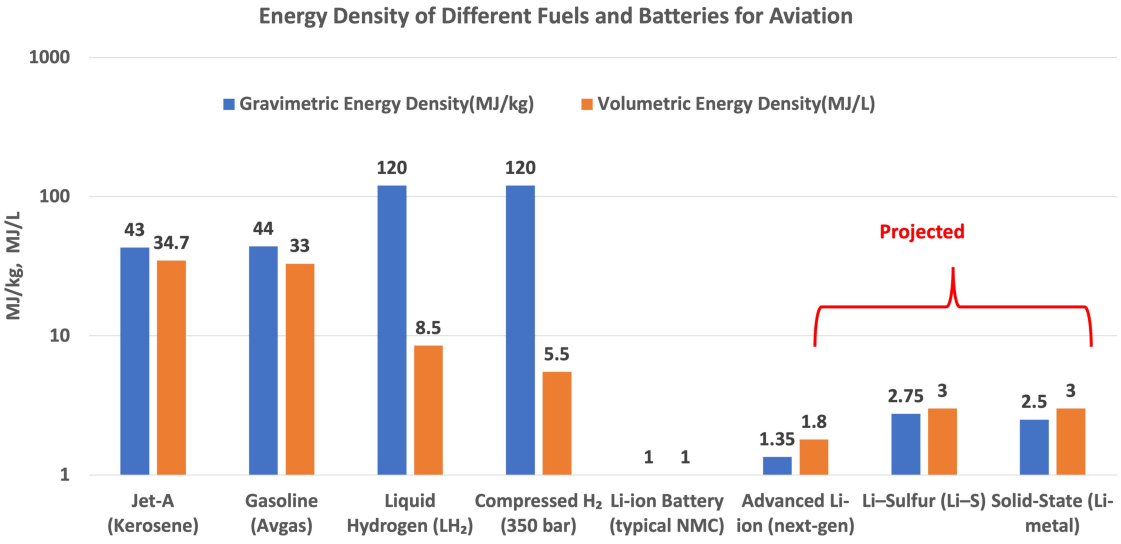


Figure 1: Comparing the energy densities of different fuels and batteries for aviation [data sources[7–10]

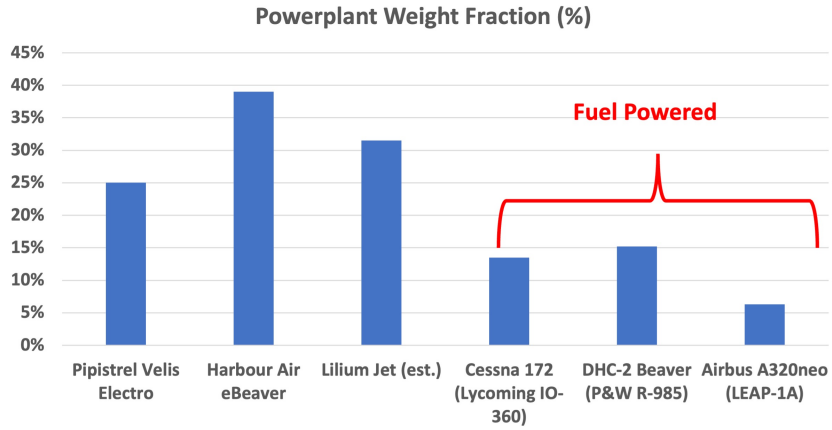


Figure 2: Comparing the powerplant weight fraction for fuel and electric powered aircraft [data source[11–14]].

The endurance and range performance of an electric aircraft fundamentally depend on three key parameters: the lift-to-drag ratio (L/D), the overall powerplant efficiency (η), and the energy capacity of the battery (E_b). Notably, electric aircraft often achieve lift-to-drag ratios that are comparable to or even exceed those of conventional fuel-powered counterparts. For example, small general aviation aircraft such as the Cessna 172 typically exhibit an L/D ratio in the range of 9 to 11,[15] whereas the electric Pipistrel Velis Electro demonstrates values ranging from 11 to 15.[16] However, despite these aerodynamic advantages, electric propulsion systems are constrained by the lower gravimetric and volumetric energy densities of current battery technologies, and their associated powerplant weight fractions. These limitations significantly impact the achievable range and payload capacity.

To explore these trade-offs, a selection of promising electric aircraft is shown in Figure 3, with key performance characteristics summarized in Table 1. For broader comparison, data for the DLR HY4, a hydrogen fuel cell-powered four-seater aircraft, is also included. Fuel cells generate electricity through an electrochemical reaction between hydrogen and oxygen, producing water as the only byproduct. This system provides a higher gravimetric energy density than conventional batteries, making it attractive for longer-range electric flight.

Figure 4 plots the range and maximum speed as a function of battery mass for each aircraft. The data suggest a near-linear relationship between battery mass and performance, indicating that larger airframes tend to achieve better

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endurance and speed due to more favorable energy storage-to-weight ratios. Notably, the DLR HY4 achieves a superior range and higher maximum speed within its class, highlighting the potential of fuel-cell systems as a promising alternative to purely battery-electric propulsion.



Figure 3: Technology Demonstrator Electric Aircraft

Aircraft	Seats	Empty Mass (kg)	MTOM (kg)	Power (kW)	Battery / Fuel-cell Mass (kg)	Cruise / Max Speed (km/h)	Range / Endurance
Pipistrel Velis Electro	2	428	600	57.6	136	~150 / —	~50 min + reserve (~60 min)
Eviation Alice	11	5000	8,346	1280	3720	~460 / ~480	~815–1,050 km
Harbour Air eBeaver	6	1361	2313	750	300	—	~82–130 km (~60–74 min)
Beta ALIA CX300	5	—	2928	350	1800	~250 / ~283	~622 km (demonstrated)
DLR HY4 (Fuel-cell)	4	630	1,500	90	630	~145 / ~200	750–1,500 km

Table 1: Comparison of pure electric aircraft performance [data source[14,16]]

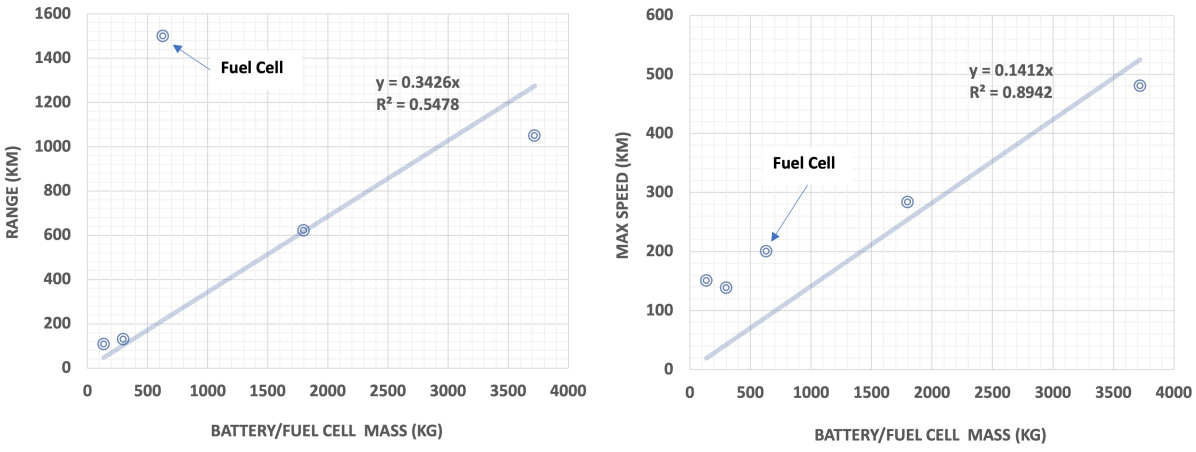


Figure 4: Performance Analysis of Technology-Demonstrator Electric Aircraft

Table 2 draws direct comparison of performance between electric and fuel powered aircraft of equivalent maximum take-off mass. IT can be deduced that the electric aircfraft significantly under perform compared to fueled

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powered, particularly the Range performance is almost 7 to 15 times lower. Maximum speed perfromance of electric aircraft is half and endurance is nearly six times less. A similar trend is observed for electric vertical take-off and landing (eVTOL) aircraft, see Table 3, many of these aircraft are experimental at this stage, hence, true perfromance data is not available. These eVTOL aircraft use distributed propulsion multi copter system allowing them to benefit from higher propulsive efficiency offered by such systems.[6, 17]

Finally, it is valuable to explore the future prospects of fully electric jetliner-class aircraft. A number of concepts and prototypes are currently under development, as summarised in Table 4. These aircraft are primarily at the conceptual design or early prototyping stage, and therefore, the performance data presented are largely projected estimates based on anticipated advancements in battery and propulsion technologies.

Despite the considerable challenges posed by the low energy density of batteries, the transition to larger aircraft appears more feasible. This is partly because the powerplant weight fraction tends to decrease with increasing aircraft size, resulting in greater mass efficiency at scale. Additionally, larger aircraft operate at higher Reynolds numbers, typically in the range of 10^7 to 10^8, which contributes to a significantly improved sectional lift-to-drag ratio due to delayed boundary layer separation and enhanced aerodynamic performance.[18]

Nonetheless, achieving full electrification at the scale of commercial airliners will require substantial technological breakthroughs in energy storage, thermal regulation, and high-voltage electrical distribution. In the near term, it is expected that hybrid-electric and hydrogen fuel cell propulsion systems will serve as transitional solutions toward the goal of zero-emission commercial aviation.[19, 20]

Parameter	Pipistrel Velis Electro (Electric)	Pipistrel Virus SW121 (Fuel)	Harbour Air eBeaver (Electric)	DHC-2 Beaver (Fuel)
MTOW [kg]	600	600	~2268	~2268
Powerplant	60 kW electric motor	Rotax 912, 75 kW	magniX 500, ~560 kW	R-985 radial, 336 kW
Cruise Speed [km/h]	100	220	~125	~220
Max Speed [km/h]	**120**	**250**	**138**	**255**
Range [km]	**108**	**1500**	**100–150**	**730**
Endurance [min]	**50**	**300**	**30–60**	**240–300**
Energy Storage	22 kWh (battery)	~80 L avgas (~720 kWh equiv.)	~300 kWh (battery)	~350 L avgas (~3150 kWh)
Specific Energy	0.2 MJ/kg	~43 MJ/kg	~0.2 MJ/kg	~43 MJ/kg
Refuel/Recharge Time	1–2 hours	5–10 minutes	~1–2 hours	5–10 minutes
Emissions (in flight)	Zero	CO_2, NOx	Zero	CO_2, NOx

Table 2: Comparing the performance of conventional fuel-powered aircraft with that of electric-powered aircraft [data source[14, 16]]

Aircraft	Seats / Payload	MTOM (kg)	Range (km)	Cruise Speed (km/h)	Max Speed (km/h)	Endurance / Time	References
Joby S4	1+4 pax (~450 kg)	~2,404	~161	—	~322	—	Joby Aviation
Supernal S-A2	1+4 pax (~450 kg)	—	~96	~193	—	—	Wired
TCab Tech E20	1+4 pax (~450 kg)	—	~200	~260	~320	—	eVTOL News
AutoFlight Prosperity	1+4 pax (~350 kg)	~2,220	~250	~200	—	—	AutoFlight
EHang EH216-S	2 pax	~620	~35	~100	~130	~25 min	EHang
Airbus Vahana	1–2 pax (~90–200 kg)	~815	~100	~200	~220	~20 min	Airbus
Beta ALIA CX300	1+4 pax	—	~460	~220	—	—	Beta Technologies
Lilium Jet (7-seater)	1+6 pax (~200–450 kg)	~3,175	~250	~280	~300	—	Lilium

Table 3: Projected performance of eVTOL aircraft

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Aircraft / Program	Type	Seats	MTOM (kg)	Range (km)	Speed (km/h)	Endurance	Reference
Elysian E9X	Battery-electric concept	~90	~36,000	~800	~500	—	Business Insider
Heart Aerospace ES-30	Hybrid-electric	30	~9,000	~320 (electric)	~270	~60–120 min	Heart Aerospace
Wright Spirit (BAe 146)	All-electric retrofit	186	~44,000	~1,100	~500	~1 hr	Wright Electric
Airbus E-Fan X	Hybrid-electric demo	100–150	~45,000 (BAe 146)	—	—	—	Airbus
Boeing X-66A (TTBW)	Hybrid-electric concept	~130–210	60,000	Long-haul	~850	—	NASA
JetZero Z4	Hybrid-electric BWB	~250	~82,000 (est.)	~8,000	~850	Long-haul	Business Insider
Airlander 10	Hybrid-lift airship	~100	~20,000–22,000	~400	~130	>5 days	The Times

Table 4: Projected performance of jetliners

3. Electric Powerplant Limitation

The mismatch between electric motor rotational speeds and optimal propeller RPM is commonly addressed using gear reduction systems, which allow high-speed electric motors to drive propellers at their most efficient speeds. However, such gearboxes introduce additional mass and mechanical complexity, as well as power transmission losses typically in the range of 3 to 5%.[21] Alternatively, direct-drive systemsâwhere the motor is coupled directly to the propellerâeliminate gearbox-related losses and mechanical complexity but may suffer from aerodynamic inefficiencies. In particular, operating a high-RPM motor directly on a large-diameter propeller can result in significant tip losses, including compressibility effects and increased noise, potentially reducing overall propulsive efficiency by up to 15%.[21–23]

To mitigate these effects, the propeller design process must be carefully optimised to balance aerodynamic performance and structural constraints. Figure 5 illustrates key principles of propeller aerodynamics, where the local blade element velocity increases with radial distance from the hub. This results in higher dynamic pressure and Mach number at the blade tips, which are the first to encounter compressibility effects. As a result, blade planform modifications such as tapering or sweepingâshown schematically in Figure 6âare employed to delay onset of compressibility effects and reduce tip losses. These geometrical adjustments also contribute to better spanwise load distribution and improved propulsive efficiency across a range of operating conditions. The other design adjustments could be to use a smaller diameter and a higher blade count.

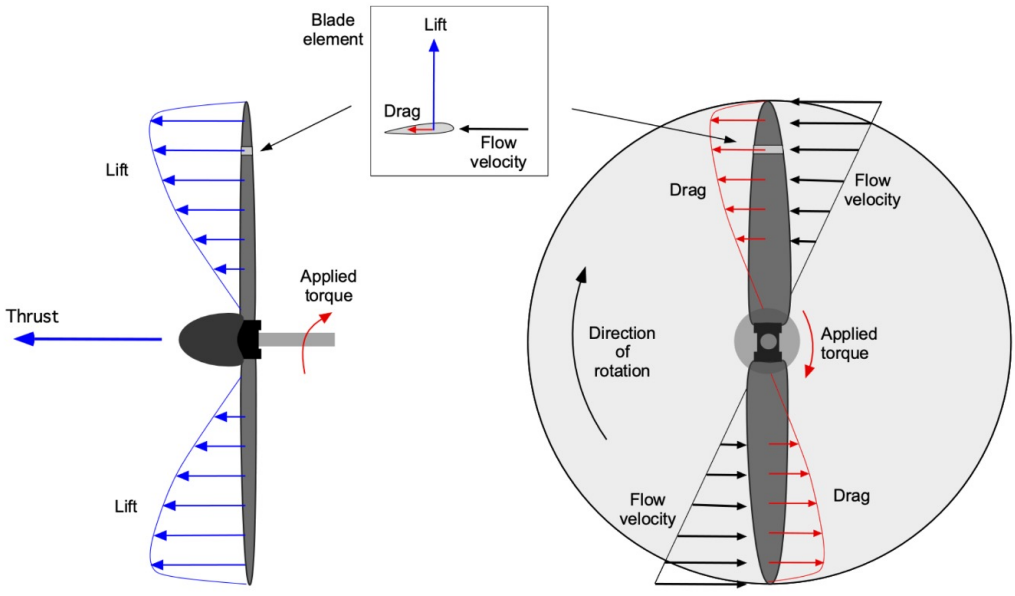


Figure 5: Fundamentals of a propeller [taken from[24]].

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RPM Range	Design Adjustments	Purpose
Low (1k–2k RPM)	Thicker chord, larger diameter, high twist	Maintain thrust at low RPM, avoid tip shock
Medium (2k–4k)	Optimised aerofoil sections, slight reduction	Maximum efficiency around cruise RPM
High (5k–10k+ RPM)	Smaller diameter, high blade count, gearbox	Used in small multicopters or with reduction gears

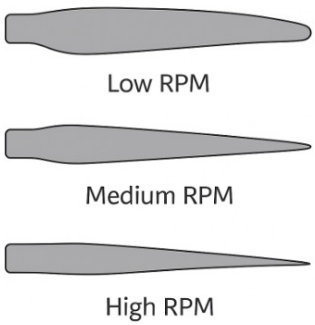


Figure 6: The effect of propeller rpm on blade geometry.

4. Geometric Derivation of a Propeller Blade

In the design of electric propulsion systems, especially where motors operate at high RPM and are directly coupled to the propeller, the blade geometry plays a critical role in maintaining efficiency across the span. This section presents a first-principles parametric formulation of blade shape, incorporating twist, chord, and sweep distributions.

Relative Velocity at Blade Element

At a radial position r, the local relative velocity experienced by a blade element arises from the combination of the axial inflow velocity v_a and the tangential speed due to rotation ωr, given by:

$$V_{\text{rel}}(r) = \sqrt{v_a^2 + (\omega r)^2} \tag{5}$$

Here, ω is the angular velocity in radians per second. In electric motors, particularly those without gear reduction, the higher ω significantly increases the tip relative velocity, which influences twist and compressibility constraints.

Blade Twist Distribution $\theta(r)$

To maintain a nearly constant optimal angle of attack α_{opt} across the span, the local blade pitch angle must satisfy:

$$\theta(r) = \tan^{-1}\left(\frac{v_a}{\omega r}\right) + \alpha_{\text{opt}} \tag{6}$$

This naturally yields a nonlinear twist distribution, with greater pitch near the root and reduced pitch towards the tip. For high-RPM electric motors, this twist gradient becomes steeper and must be considered in both aerodynamic and structural design.

Chord Distribution $c(r)$

Assuming a uniform thrust loading or elliptical lift distribution (for optimal efficiency), the local chord can be derived from blade element theory as:

$$c(r) = \frac{2T}{N_b \rho V_{\text{rel}}^2(r) C_L r} \tag{7}$$

where:

- T is the total propeller thrust,
- N_b is the number of blades,
- ρ is the air density,

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- C_L is the sectional lift coefficient.

Alternatively, using a non-dimensional thrust coefficient C_T, and normalising with respect to the propeller radius R, the chord distribution simplifies to:

$$c(r) = \frac{C_T}{\pi R} \cdot \frac{1}{C_L \cdot r} \tag{8}$$

This inverse dependence on r implies a larger root chord and smaller tip chord, aligning well with structural stiffness and manufacturing feasibility.

Sweep Distribution $\Lambda(r)$

Blade sweep is introduced either for compressibility relief (at high tip Mach numbers) or to manage aeroelastic effects. It can be defined empirically as:

$$\Lambda(r) = \Lambda_{\text{tip}} \left(\frac{r}{R} \right)^n \tag{9}$$

where:

- Λ_{tip}: tip sweep angle (in degrees),
- n: sweep exponent (commonly 1â2 depending on structural and aerodynamic trade-offs).

Parametric Blade Geometry Summary

The full parametric blade shape can be represented as a system:

$$\begin{cases} c(r) = \dfrac{C_T}{\pi R} \cdot \dfrac{1}{C_L \cdot r} \\ \theta(r) = \tan^{-1}\left(\dfrac{v_a}{\omega r} \right) + \alpha_{\text{opt}} \\ \Lambda(r) = \Lambda_{\text{tip}} \left(\dfrac{r}{R} \right)^n \end{cases}$$

For high-RPM electric motors, as typically used in small- to mid-scale eVTOL and UAV applications, this formulation informs the trade-off between aerodynamic efficiency and blade manufacturing constraints. In distributed propulsion systemsâwhere propellers are smaller and operate at moderate tip speedsâthe required blade twist is minimal, simplifying the design.

5. Upper Surface Blowing as a Solution to Propeller RPM Mismatch: A Theoretical Foundation

To achieve an elliptical lift distribution on a high RPM propeller blade through leading-edge upper surface blowing, we can use the concept of circulation and the Biot-Savart law along with the lift distribution equation. The concept here is to control the lift distribution by blowing air over the upper surface of the blades.

The lift distribution $L(y)$ along the blade can be defined by an elliptical distribution as follows:

$$L(y) = L_{total} \left(1 - \left(\frac{2y}{b} \right)^2 \right)$$

where: - $L(y)$ is the local lift per unit span at a distance y from the blade root, - L_{total} is the total lift generated by the blade, - b is the total span of the blade, - y is the distance from the root of the blade.

To incorporate leading-edge blowing, we can relate the blowing velocity V_b at the leading edge to the desired lift distribution. The effective angle of attack α_{eff} is modified by the blowing, which increases the effective lift coefficient C_L.

The formula considering blowing can be expressed with an effective lift coefficient $C_{L,eff}$:

$$C_{L,eff} = C_L(\alpha) + kV_b/V_\infty$$

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where: - $C_{L,eff}$ is the modified lift coefficient due to blowing, - $C_L(\alpha)$ is the lift coefficient at angle of attack α, - V_b is the blowing velocity at the leading edge, - V_∞ is the free-stream velocity, - k is a constant that relates the blowing to the increase in lift (empirical or derived from experimental data).

Thus, the lift acting on a differential section of the blade can be expressed as:

$$dL = \frac{1}{2}\rho V^2 C_{L,eff}(y)c(y)dy$$

where: - dL is the differential lift, - ρ is the air density, - V is the velocity at that section of the blade, - $C_{L,eff}(y)$ is the effective lift coefficient incorporating the blowing, - $c(y)$ is the chord length at distance y, - dy is the differential spanwise length.

By adjusting the blowing velocity and its distribution along the chord of the blade, we can effectively achieve the desired elliptical lift distribution, enhancing performance at high RPM conditions.

In summary, the essential equations involve determining the elliptical lift distribution, accounting for the specific effects of leading-edge blowing, and relating them through effective angles of attack and lift coefficients.

6. Conclusions

There are two primary limitations currently impeding the realisation of electric-powered aircraft for commercial aviation. First, the gravimetric and volumetric energy densities of existing battery technologiesâparticularly lithium-ionâare significantly lower than those of conventional aviation fuels. This leads to disproportionately high powerplant weight fractions, which directly compromise endurance, range, and cruise performance. While emerging battery chemistries may offer up to a threefold increase in energy density, they remain at a developmental stage.

Interestingly, scalability trends indicate that larger aircraft may be better suited to electric propulsion. As battery capacity increases, the relative powerplant weight fraction tends to decrease, and larger aircraft benefit from operating at higher Reynolds numbers (on the order of 10^7 to 10^8). These conditions favour higher sectional lift-to-drag ratios, thus partially offsetting energy density limitations through aerodynamic efficiency.

The second key limitation is the efficiency loss associated with the mismatch between motor and propeller rotational speeds. Conventional solutions such as gearboxes introduce mechanical losses and additional weight. However, based on blade element theory, an alternative approach involving leading-edge upper-surface blowing has been proposed to achieve an elliptical lift distribution at high rotational speeds. A preliminary analytical model has been developed to support this concept, offering a foundation for further aerodynamic and propulsion optimisation research.

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