TRANSACTIONS ON AEROSPACE RESEARCH
eISSN 2545-2835, VOL. 277, NO. 4/2024, 14-26
DOI: 10.2478/tar-2024-0020

REGIONAL PASSENGER AIRCRAFT TYPE OF AN-158 WITH A HYBRID PROPULSION PARAMETRIC CONCEPT

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ABSTRACT

This study proposes a concept for the design and development of a modification of the An-158 regional passenger aircraft equipped with a hybrid propulsion system. The propulsion configuration includes two turboprop engines and two electric engines, with multidirectional propellers positioned symmetrically at the wing tips. This innovative design reduces wingtip vortices, decreasing inductive drag and improving aerodynamic efficiency. Parametric analyses were conducted using the modular software systems "Integration 2.1" and "Propeller 2.2" for typical flight profiles of the An-158. Despite the added weight from hybrid components, the modified aircraft design demonstrated reduced fuel consumption and harmful emissions in taxiing, takeoff, and climb modes. These findings highlight the potential of hybrid propulsion to enhance environmental performance while maintaining operational efficiency.

Keywords

aircraft, regional aircraft, turboprop engine, harmful emissions, propeller, hybrid propulsion.

1. INTRODUCTION

Increasingly stringent ICAO regulations regarding the environmental impact of aviation are stimulating intensive research into innovative propulsion technologies, including hybrid propulsion (HP). As highlighted in [1, 2], hybrid propulsion systems hold immense potential for improving fuel efficiency, reducing emissions

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Received 22.12.2021 • Revised 13.06.2024 • Accepted 26.06.2024

and minimizing noise levels. The adoption of hybrid propulsion, however, necessitates the complex integration of flight propulsion and aircraft airframe subsystems, requiring thorough investigation of the "propeller–wing–nacelle" or "propeller–fuselage–nacelle" system [3, 4]. Such research involves exploring new structural and layout schemes for aircraft and flight propulsion systems, aiming to improve their integral properties and to develop scientific and technical directions for creating effective hybrid propulsion, which will include electric engines of various capacities. Research into hybrid propulsion aircraft emphasizes increasing fuel efficiency and reducing the negative impact on the environment, in line with the goals for next-aviation generation. This study proposes a concept for the design and development of a modification of the An-158 regional passenger aircraft equipped with a hybrid propulsion system.

List of symbols

M	Mach number
M_{max}	Mach number maximum
D_{prop}	Diameter of the propeller (m)
H	Altitude of flight (m)
L_{max}	Range maximum with weight of fuel maximum (km)
L_{TO}	Takeoff distance (m)
P_{eng}	Power engine (hp)
T_{prop}	Thrust of propeller (kg)
K	Aerodynamic quality
$\bar{b}$	Blade relative chord
q	Kilometer fuel consumption at cruise mode (kg/km)
Q	kilometer fuel consumption at cruise per passenger (gram/pass)
W_{fuel}	Weight of fuel (kg)

2. LITERATURE REVIEW

Newly developed structural and layout schemes for aircraft frequently build on the advantages of well-known aircraft aerodynamic designs – like, for instance, the modifications made to well-known aircraft such as the A320 and B737 [5, 6]. Boeing and Embraer are considering the possibility of launching new aircraft with turboprop engines (TPE) based on modern technologies [7]. Embraer is negotiating with General Electric, Pratt & Whitney, and Rolls-Royce for engine supplies for the first two such aircraft. However, despite the high efficiency of aircraft with turboprop engines during takeoff and landing, the market has for a long time remained without new versions of this type of aircraft. These industry efforts exemplify the broader push for sustainable aviation solutions, setting the stage for a deeper exploration of technical challenges and opportunities. This section reviews the relevant literature.

Today's turboprop aircraft market is dominated by ATR, which accounts for about 75% of the aircraft in the sector. Its designs have undergone various changes over the years, but the layout of the aircraft has remained the same. Since 2016, however, Embraer has begun to develop a new turboprop aircraft [8], with a cabin comparable to that of an E-Jet, featuring low noise and vibration levels – a cabin larger than that of many turboprop aircraft. The aircraft is meant to accommodate 80–100 passengers, which is more than the deHavilland Canada Q400 and ATR 72, allowing it to compete with smaller aircraft such as Embraer's own E175 E2 [9]. Additionally, this new aircraft will have a traditional design aimed to reduce per-seat fuel consumption by 15–20% compared to existing aircraft, and it will be designed so that components for a hybrid scheme can be added in the future. New technologies will be gradually introduced into the turboprop engine, and this will significantly reduce harmful carbon emissions by 2050 [10, 11].

The auxiliary electrical system's impact on the engine performance of A320 aircraft when flying over short distances has been studied [12], with a developed simulation model consisting of an aircraft performance model combined with an engine model. It was found that electrically actuated flight propulsion can reduce fuel consumption, total energy consumption and harmful emissions for short-distance flights of about 1000 km.

Similarly, the study in [13] describes a solution for reducing harmful emissions and noise in the vicinity of airports, focusing on regional passenger aircraft. It outlines aircraft specifications and market requirements that match real-world air transport sectors with the most appropriate implementation of all-electric or hybrid aircraft. While the study highlights the development of regional aircraft with hybrid propulsion, it does not provide quantitative indicators of the feasibility of using hybrid turboprop engines.

The study in [14] reviews the current state of aircraft engine development and explores critical technological advancements for next-generation aviation systems internationally. It identifies various concepts for hybrid (turboelectric) and fully electric propulsion systems, projected for the medium and long term (2030–2040) highlighting significant progress in the development of electrical system components [15]. Additionally, it discusses aircraft concepts incorporating components based on high-temperature superconductivity. However, this study does not address the issues of modernizing existing aviation technology to reduce the cost per flight hour.

Future directions for development include six key propulsion architectures [14]: fully electric, hybrid (parallel hybrid, serial hybrid, parallel partial hybrid) and turboelectric (fully turboelectric, partly turboelectric). These configurations rely on diverse electrical technologies (batteries, motors, generators, etc.). However, this work does not quantify the CO_2 emission reductions associated with different architectures, configurations, component characteristics and tasks.

For regional and large aircraft, design configurations are categorized into three main groups: partially turboelectric, fully turboelectric, and hybrid electric [16]. Fully electrical systems rely on batteries as the sole source of energy. Hybrid systems use gas turbine engines for propulsion and battery charging, with batteries also providing energy to propel the aircraft during one or more phases of flight.

The studies in [17, 18] explore regional hybrid electric aircraft powered exclusively by batteries, focusing on hybrid propulsion strategies. They particularly analyze the role of the battery in environmentally friendly concepts aimed at a significantly reduced carbon footprint. Key findings emphasize the importance of selecting an optimal power-to-battery ratio for different flight cycles. However, these studies do not address how to determine the technological feasibility of hybrid concepts. Similarly, over the next 30-year period, the same uncertainties apply to emerging technologies such as superconducting engines and generators, fuel cells and cryogenic fuels [19, 20].

The work in [21] reviews and analyzes various concepts, models and design approaches for electric, hybrid and turboelectric fixed-wing aircraft. It also considers the application of distributed electric traction technologies for advanced aircraft [22, 23], providing examples of integrating high-thrust engines into new aircraft design configurations [24, 25].

The article in [26] presents a concept for modernization of the An-26 and An-140 aircraft by incorporating hybrid basic propulsion. This research focuses on transport and passenger categories in the 20–25 ton weight range. One proposed modernization approach involves equipping these aircraft with hybrid propulsion systems comprising a gas turbine and a power electric engine, which drives the propeller. The findings demonstrate significant improvements in flight performance and compliance with modern and projected environmental standards.

The study in [27] investigates the operating characteristics of bypass turbofan engines in a parallel hybrid-electric propulsion system. In this configuration, electric engines are used to supply energy during the most difficult stages of takeoff and climb to achieve the required thrust, enabling the bypass turbofan engines to achieve maximum cruise performance. The findings indicate that the efficiency of bypass turbofan engines can be increased by 1% due to the reduced restrictions on takeoff and climb. In short-haul flights, hybrid electric propulsion has demonstrated the potential to reduce fuel consumption for A320 aircraft by about 7%, though the majority of these savings come from all-electric steering. The study concludes that parallel hybrid-electric propulsion is unlikely to be adopted in the next-generation aircraft for short and medium flight ranges.

The research in [28] focuses on the possibility of creating a hybrid-electric aircraft with 19 passenger capacity, to serve the short-haul segment ranging from 200 to 600 nautical miles. It introduces an energy storage positioning methodology to highlight the multidisciplinary considerations of aircraft size, propulsion architecture (serial/parallel partial hybrid) and energy storage performance. The results reveal that achieving the original design goal of 600 nautical miles with a fully electric aircraft is infeasible due to the excessive battery capacity required. Furthermore, the study highlights that a lower hybridization rate (40%) offers superior energy efficiency, with 12% lower energy consumption and greater CO_2 reduction compared to a configuration with a higher hybridization rate (50%) than the traditional scheme.

The article in [29] examines the impact of distributed hybrid electric propulsion on the flight performance of aircraft with a capacity of 150 passengers and a flight range of approx. 1500 km. A novel method of preliminary sizing of hybrid electric aircraft with distributed propulsion was employed. The findings revealed a significant increase in the flight propulsion system across all designs. Additionally, an aircraft utilizing a distributed flight propulsion was found to exhibit up to a 51% increase in energy compared to conventional bypass turbofan engines.

The study in [30] evaluates the options for a mechanically integrated parallel hybrid propulsion system. Alongside defining the basic flight propulsion characteristics, the research develops an architectural framework for the electrical systems, detailing the main electrical components involved as well as important aspects of integration with the airframe. Flight propulsion and power distribution components are sized, and efficiency and weight are evaluated with reference to thermal management requirements. The overall system assessment includes an evaluation of the potential for fuel savings based on a parametric study of aircraft dimensions, including the identification of key technology requirements for on-board electrical storage. However, this research does not provide a comparative analysis of the structural materials (e.g., composites vs. metals) used in modern aircraft structures, which is critical in selecting the optimal design for hybrid propulsion systems [31].

The work in [32] compares and contrasts electric traction and other breakthrough technologies in aircraft design tools. It highlights that integration of an electric propulsion will involve a much greater degree of distribution than existing propulsion systems. The articles in [33–36] analyze the design of a hybrid electric engine for passenger regional commercial aircraft, although specific flight segments where there is a benefit from the hybrid propulsion use are not indicated. The article in [37] models and examines a turboprop hybrid electric propulsion, analyzing optimal parameters for design and operation in different flight modes.

Overall, the reviewed literature highlights the scientific and practical significance of developing a parametric design framework for regional passenger aircraft with hybrid propulsion systems. This body of work addresses critical gaps in existing research, particularly concerning the technological feasibility, optimization of flight cycle parameters, and the selection of structural materials. By advancing these areas, future research can enhance the efficiency, sustainability, and overall performance of next-generation hybrid aircraft, contributing to the broader goal of more environmentally friendly aviation.

3. THE PURPOSE AND OBJECTIVES OF THE RESEARCH

The aim of this study was to substantiate the parametric design framework for a regional passenger aircraft of the An-158 type with hybrid propulsion. To achieve this, the following objectives were defined:

– to analyze the current state and development priorities of regional passenger aircraft with hybrid propulsion;
– to investigate the flight performance and characteristics of the base aircraft An-158, a modified An-158 aircraft with turboprop engines (An-158-TPE), and a modified An-158 aircraft with hybrid propulsion (An-158-HP).

4. THE RESULT OF THE AIRCRAFT MODIFICATION CHARACTERICTICS RESEARCH

To develop the parametric framework of a regional passenger aircraft with hybrid propulsion, this study first analyzed the characteristics of the base An-158 passenger aircraft [38] (Fig. 1), as well as a modified version of the An-158 aircraft, the An-158-TPE, equipped with two turboprop engines, positioned in front of the wing (as pulling propellers), symmetrically aligned with the fuselage axis (Fig. 2).

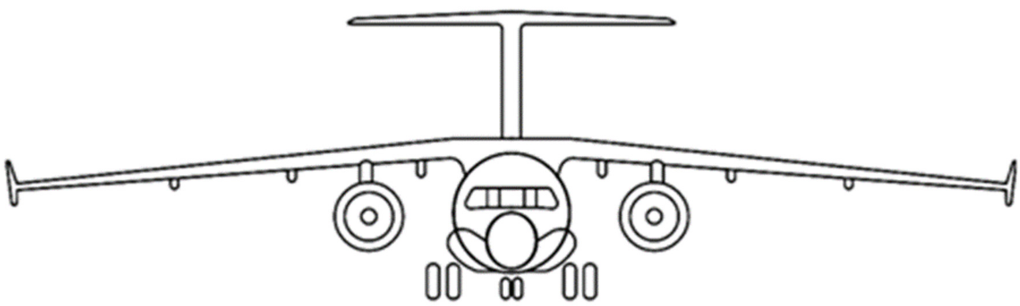


Fig. 1. The base An-158 aircraft.

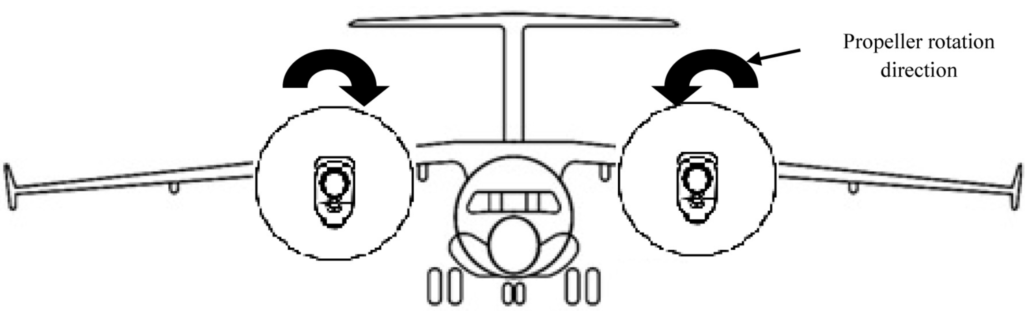


Fig. 2. The An-158-TPE modification of the An-158 type aircraft with turboprop engines.

Next, the study considered the design with a hybrid propulsion system, the An-158-HP, which includes two turboprop engines alongside two electric engines, with multidirectional propeller rotation, located at the ends of the wing, symmetrically aligned with the fuselage axis (Fig. 3).

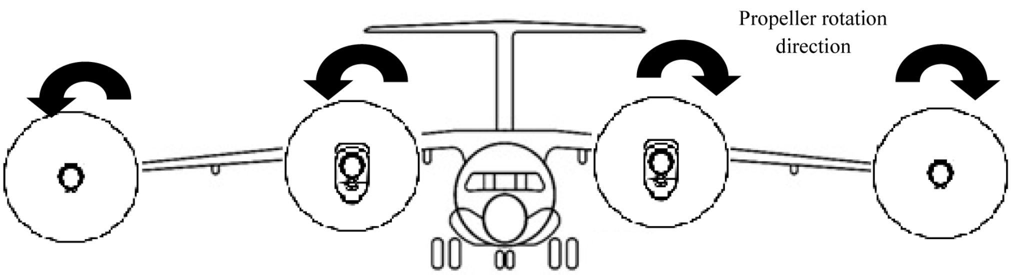


Fig. 3. The An-158-HP modification of the An-158 type aircraft with hybrid propulsion.

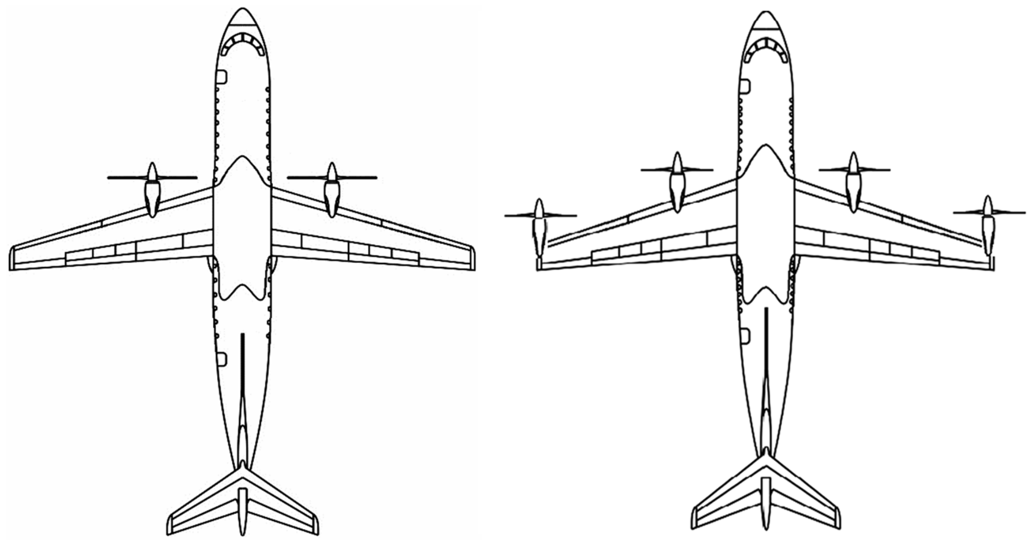
It is well established that propellers rotating in the same direction create an asymmetric distribution of circulation over the aircraft wing. This asymmetry leads to imbalances in the aircraft along its three axes during changes in engine operating mode. Using counter-rotating propellers mitigates these effects. In this configuration, the local angles of attack in the blown sections of the wing are increased, enhancing lift in these sections. This is particularly beneficial for optimizing the takeoff and landing characteristics of the aircraft. With counter-rotating propellers, the dissymmetry of the flow and the roll moment will disappear, the parrying of which causes an increase in resistance. Based on a decrease in the intensity of the end vortices, the inductive resistance will decrease. Reducing the inductive drag allows the cruising aerodynamic quality of the aircraft to be increased by about 2 units, as confirmed by wind tunnel experiments.

Increasing the number of propeller blades, while maintaining constant thrust during the takeoff mode, reduces the aerodynamic load acting on the blade and, accordingly, decreases in the harmonic noise component from the aerodynamic load. Additionally, the frequencies of harmonic components to the high-frequency region are shifted.

The initial parameters, limitations, and research methods for optimizing the aerodynamic characteristics of the propellers were selected with consideration for all the operating modes of the turboprop engine in a regional passenger aircraft. For this study, a modification of the An-158 type aircraft, designed to accommodate 100 passengers, was developed (Fig. 4).

Fig. 4. Modification of the An-158 type aircraft .

Based on the analysis of requirements for passenger category aircraft modifications and preliminary research into takeoff and landing characteristics and weight calculations, the structural layout of the aircraft with the hybrid propulsion, which has distinctive layout features, was preliminarily formulated (Fig. 5). The weight data for the modifications are presented in Table 1.



a b

Fig. 5. Modifications of the An-158 type aircraft: (a) with turboprop engine, (b) with hybrid propulsion.

Table. 1. Results of coercive force measurements.

Operational empty weight, kg	Gross weight, kg	Aircraft name	Payload weight, kg	Aircraft flight propulsion weight, kg
10000	5476	24583	43733	An-158-TPE
10000	9645	29169	48319	An-158-HP

The initial data for propeller design calculations for the turboprop engine are as follows: the maximum required power of one engine during level flight, the altitude and speed of level flight, the revolutions per minute of the engine output shaft, and design restrictions on the diameter of the propeller. Quantitative parameters for designing propellers with different numbers of blades were defined as follows: flight altitude H=9000 m; flight speed V=745 km/h; engine output shaft speed n=850 rpm; engine power N_{eng}=4300 hp; propeller diameter D_{prop}=4.5 m; blade material: composite.

The performance characteristics of propellers with varying blade numbers (k = 4, 6, 8, 10) were investigated for these flight conditions. It was found that choosing fewer than 8 blades in the propeller composition is not advisable due to insufficient blade elongation, low efficiency, etc. At this stage, the number of blades k was selected to maximize the relative blade chord $\bar{b}_{max}$ within the recommended range of 0.1 to 0.2. Beyond $\bar{b}_{max} > 0.2$ the inductive power consumption increases significantly, reducing propeller efficiency due to the small elongation of the blades.

To establish the hybrid propulsion configuration for the An-158 modification, a method for determining design weight and takeoff characteristics was developed. This method considers various types of engine as part of the flight propulsion system. The key characteristics for evaluating structural and layout schemes include:

– aircraft fuel efficiency with the specified flight propulsion configuration;
– estimated flight range and duration;
– variation range in the “load – range” diagram;
– maximum flight speed;
– takeoff and landing characteristics;
– weight and dimensional characteristics of the aircraft.

The investigation of aircraft characteristics was carried out using the modular software package “Integration-2.1” following the methodology described in [39, 40]. This modular software package was developed for parametric studies of aircraft performance at the modernization or preliminary design stages. It includes computational program blocks that are interconnected, making it possible to study the characteristics of aircraft with various propulsion systems, including both bypass turbofan engines and turboprop engines.

A typical flight profile was investigated for an estimated flight range of L=2500 km, a cruise flight altitude of H=9000 meters, and a cruise Mach number of M=0.68. For the hybrid propulsion modification, the required battery capacity and the weight of their cooling system were calculated to support for two electric engines with an equivalent power of P=1000 hp, used for taxiing, takeoff, and climb.

The main research results are shown in Table 2.

Table. 2. Main characteristics of aircraft modifications.

Parameter	Aircraft modification		
	An-158	An-158-TPE	An-158-HP
q, kg/km (specific fuel consumption per km)	2.394	2.406	2.552
Q, gram/pass (fuel consumption per passenger)	26.6	24.058	25.53
$K \times M$ (efficiency coefficient)	8.66	8.965	9.221
$P_{eng\,1}$, hp (average power of one engine required for level flight)	-	4057	4306
$T_{prop\,1}$, kg (average thrust of one propeller required for level flight)	-	1575	1671
W_{fuel}, kg (total fuel consumption for the entire flight)	7100	7618	7532
W_{fuel}, kg (total fuel consumption for level flight)	4811	4797	5017
L_{TO}, m (takeoff distance)	1410	1372	1535

Placing electric engines at the wing tips enhances the aerodynamic layout of the aircraft, improving its overall efficiency. Structural adjustments increase the effective wing aspect ratio, while engine nacelles at the wing tips help reduce overflow spillage from the underside of the wing to the upper surface. Additionally, counter-rotating propellers generate swirling jets that diminish the intensity of the end vortices, thereby reducing the wig's inductive drag (by an estimated 10–15%).

Despite the increased weight of aircraft modifications with hybrid propulsion, the improved aircraft layout contributes to a reduction in fuel consumption and harmful emissions (in taxiing, takeoff, and climb modes, fuel consumption was reduced by more than 300 kg).

The benefits of hybrid propulsion are more pronounced with shorter flight range and duration. However, on longer segments, the aircraft incurs slightly higher per-kilometer costs (25.53 grams/km per passenger for the hybrid configuration versus 26.6 grams/km per passenger for the base aircraft) due to the increased flight mass.

This study did not fully explore the potential advantages of hybrid propulsion, as several factors were not accounted for, including improvement of the aerodynamic quality in flight modes, in-flight recharging of batteries, the elimination of on-board batteries in the basic modification, energy recovery during descent and on the run of the aircraft. Moreover, the study did not investigate the possibility of developing a single-mode turboprop engine, which could reduce the weight and fuel consumption.

5. CONCLUSIONS

This study has proposed a parametric framework for a hybrid propulsion system in a regional passenger aircraft of the An-158 type. Preliminary calculations and analysis of the development priorities for such a regional passenger aircraft with hybrid propulsion were performed. A comprehensive method for determining the characteristics of the range and duration in a typical flight of this passenger aircraft has been improved. Preliminary results of the flight characteristics of the An-158 type modified aircraft with hybrid propulsion were obtained.

The hybrid propulsion system, featuring counter-rotating propellers located at the wing tips, was found to effectively reduce inductive drag by up to 15%. This improvement enhanced the aerodynamic efficiency of the aircraft. While the hybrid propulsion configuration increased the aircraft's overall weight, it resulted in reduced fuel consumption and harmful emissions during critical flight phases such as taxiing, takeoff, and climb. However, the slightly higher per-kilometer fuel consumption for extended flight ranges remains a trade-off due to the additional weight. Due to its greater takeoff weight, the aircraft with the hybrid propulsion system has a greater takeoff distance compared to the base modification (1535 m versus 1372 m for the base modification). This increase in the takeoff mass of the aircraft is not fully offset by the increased in the airflow surface of the wing. However, this study did not explore the potential application of using blown hover flaps, which can significantly reduce the takeoff distance. Structural and aerodynamic enhancements, including the optimized wing-tip engine nacelle placement, contributed to overall performance improvements. The integration of these design elements offset some weight-related penalties and underscored the potential of hybrid systems for sustainable aviation.

Potential directions for future research include the following:

- conducting a quantitative assessment of noise reduction potential for aircraft equipped with hybrid propulsion systems,
- performing theoretical and experimental studies to enhance aerodynamic performance, focusing on counter-rotating propellers optimized for climb modes,

- investigating energy recovery mechanisms, including the recuperation of propeller energy during descent and in-flight battery recharging using onboard generators,
- exploring the development of specialized propellers for hybrid propulsion.

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