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REGIONAL TRANSPORT AIRCRAFT DESIGN USING TURBO-ELECTRIC DISTRIBUTED PROPULSION (TEDIP) SYSTEM

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Abstract

As the world moves towards environmental sustainability, the civil aviation enterprise has responded by setting challenging goals for significantly increased energy efficiency and reduced harmful emissions into the atmosphere. Many government agencies and the aviation industry support these goals because of their positive impact on operational cost and the environment. Achieving the goals requires introduction of aircraft concepts with novel technologies. Examples of novel technologies include alternative fuels such as hydrogen; all-electric, hybrid-electric and turbo-electric propulsion systems; distributed propulsion and boundary-layer ingestion. In this paper, the authors present the findings of their research to integrate two technologies, namely, turbo-electric propulsion and distributed propulsion, into a baseline twin-propeller regional transport aircraft, the ATR 72-500, with a nominal range of 1,500 km; cruise speed of 510 km/hour; and a nominal payload of 68 passengers. Three variants with four, six, and eight propellers are designed, and their performance for a prescribed mission is compared to that of the baseline in order to assess their relative benefits and penalties against the baseline.

Keywords: Turbo-electric propulsion; distributed propulsion; regional transport aircraft; wing-propeller interaction

1. Introduction

Changes in the world's transportation systems are being prompted by rising fossil fuel costs and growing environmental concerns. To power land-based modes of transportation, alternative energy sources such as bio-fuels and turbo/hybrid/fully electric systems are being investigated. The aviation industry is also actively involved in trade space exploration of novel propulsion concepts integration. The aviation industry is responsible for 2.1% of all human-induced CO_2 emissions which demands a renewed emphasis on reducing its environmental impact. In addition, fuel price volatility coupled with a greater demand for air travel have heightened interest in improving fuel economy and lowering emissions for aircraft. The need of novel propulsion concepts for aviation is driven mainly by its potential to mitigate the environmental impact of aircraft that use hydrocarbon fuel.

The civil aviation enterprise has responded by setting challenging goals for significantly increased energy efficiency and reduced harmful emissions into the atmosphere as codified by NASA [1]. ACARE [2] has presented ambitious plans to reduce CO_2 emissions per passenger kilometer by up to 75% and NO_x by 90% by 2050. The airline industry supports these goals because of their positive impact on operational cost from reductions in fossil fuel burn and the resulting environmental benefits. Achieving these goals requires introduction of novel technologies and aircraft concepts. Figure 1 illustrates one such concept by Rolls-Royce in the U.K. with a modern implementation of the distributed

Figure 1. Rolls-Royce Distributed Open Rotor Aircraft concept for regional aircraft. © 2016 Rolls-Royce, plc.

propulsion (DiP) technology.

Previous studies have shown that electrified aircraft can be effective in meeting the challenges of improved energy efficiency and environmental sustainability [3-9]. Moore and Fredericks [3] leveraged distributed electric propulsion (DEP) technology to demonstrate the feasibility of electrically powered aircraft. Gohardani [4] suggested that effective use of DEP could be a game changing technology for introduction of alternative propulsion systems for general aviation aircraft.

For electrified aircraft, propulsion architectures fall in three main categories: (i) all electric; (ii) hybrid electric; and (iii) turbo-electric. All electric aircraft, using batteries as the sole source of energy, are not likely to be practical without significant technology improvements that dramatically increase battery energy density [5]. This is not surprising because the specific energy of today's batteries is nearly 1/18th that of hydrocarbon fuels. Hybrid electric aircraft, using a combination of turbine engines and batteries to provide the required power, offer an attractive alternative. However, their feasibility and practicality are strongly dependent on the battery energy density as Ganesh et al [6] demonstrated by integrating a hybrid electric distributed propulsion system into a 19-Passenger Twin Otter aircraft. Turbo-electric propulsion systems completely dispense with battery, but allow leveraging other technologies, such as DiP [7-9]. This motivated the authors to undertake the present study for integrating a turbo-electric system with distributed propulsion into a 70-passenger class of regional transport aircraft (RTA).

In a turbo-electric architecture, shown in Figure 2, gas turbines drive generators to generate electricity to power electric motors that drive propellers. Because of energy conversion and transmission losses, turbo-electric architectures are inherently less efficient than conventional gas turbine propulsion as shown in Figures 3(a) and 3(b). Note that the system-level efficiencies are calculated by multiplying component efficiencies; propeller is not included in the powertrains shown in Figures 3(a) and 3(b).

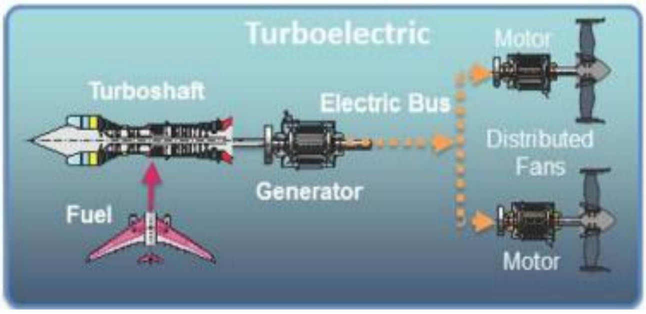

Figure 2. Turbo-electric architecture schematic [2]

For the turbo-electric propulsion to be beneficial, we need to leverage other technologies like DiP. However, there are several challenges for implementing DiP into an airframe including choosing the total number of propellers for optimum efficiency; operational scheduling of the multiple propeller units during different flight segments; the best set of components for the electrical system to power the propellers to name a few. We also need to exploit continuing advancements in technologies for generators, motors, power distribution, and power electronics (converters, inverters and circuit protection). Additional integration challenges relate to cooling of components. We address these challenges to various levels of approximation in this study.

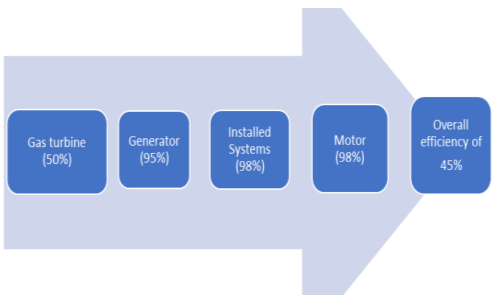

Figure 3(a). Schematic of turbo-electric system efficiency

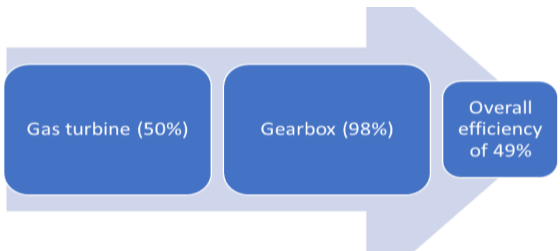

Figure 3(a). Schematic of turboprop efficiency

The scope of the present research covers integration of a turbo-electric distributed propulsion (TEDiP) system into a baseline RTA that is currently operational. The overall objective is to evaluate its benefits and shortcomings compared to the baseline turboprop. We have selected the ATR 72-500 as the baseline aircraft. It has a nominal range of 772 nautical miles (1,500 km) at a cruise speed of 275 KTAS (510 km per hour) with a full load of 68 passengers. A picture of the aircraft in flight is shown in Figure 4(a), and a nominal mission profile in Figure 4(b).

Figure 4(a). The ATR 72-500

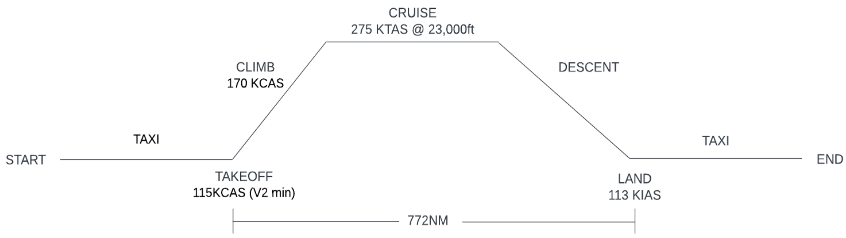

Figure 4(b). ATR 72-500 nominal mission profile

The three specific objectives of this research are:

1. To design variants of the ATR 72-500 aircraft with TEDiP system using a mature multidisciplinary design, analysis and optimization (MDAO) framework.
2. To support design of all variants by generating aerodynamic data using fast and cost effective analysis methods.
3. To evaluate potential benefits and penalties of TEDiP variants using the ATR 72-500 as baseline.

The remainder of the paper is organized as follows. The authors highlight their technical approach and methodology in Section 2. This is followed by results and discussion in Section 3. A few concluding remarks in Section 4 complete the paper.

2. Technical Approach and Methodology

The technical approach to achieving the objectives requires developing a suitable TEDiP system and integrating it into an ATR 72-500 aircraft. The TEDiP system itself requires combining (i) a turbo-shaft engine with an electric generator, and (ii) distributed propulsion technology using multiple motor-propeller units. Integration of the resulting TEDiP system into an airframe should leverage the well-known favorable interference between the wing and [tractor] propeller wake to provide increased lift for takeoff. Our focus in on conducting a conceptual level study using a mature MDAO framework to facilitate expeditious exploration of multiple feasible design options through trade studies.

The methodology to implement the technical approach is a two-step process: (1) use a MDAO framework to design TEDiP variants of the ATR 72-500 by integrating multiple propellers powered by a turbo-electric system; and (2) evaluate the flight performance of the variants and compare with that of the baseline. We have selected the Pacelab Aircraft Preliminary Design (APD) framework [10], a robust and effective suite of MDAO software, to conduct both steps of the process. Ganesh et al. [6] demonstrated the potential of the APD framework by integrating a hybrid-electric propulsion system into a small RTA. APD is the product of a German company, PACE GmbH, now a part of TXT. For this research, PACE provided access to the state-of-the-art versions of the software.

2.1 Pacelab APD

Several MDAO frameworks exist for aircraft design studies including OpenMDAO and Flight Optimization System (FLOPS) by NASA, and Aircraft Preliminary Design (APD) by Pacelab. All these have been, and are being, extensively used. The Pacelab APD was selected for the present study based on the experiences of other VT researchers [6] that cite APD’s key desirable characteristics as capability, modularity, maturity, ease of update, reliability, and graphical user interface (GUI).

APD is widely used by researchers and innovators worldwide. Its underlying approach is based on declarative design where a user decides the design methodology by prescribing the parameters that should be input and those that could be estimated by built-in methods. One of the interesting features of APD is a unique “solution engine” that offers a plethora of analysis and design possibilities. Another useful feature is the ability to rapidly setup design sensitivity studies; this is particularly useful in design space exploration of novel aircraft designs.

APD offers a powerful GUI, shown in Figure 5, with a structured and easy to understand parameter prescription interface. APD’s built-in aerodynamics and weights modules are based on the parametric approaches of Torenbeek [11] and Raymer [12]. APD also leverages its extensive database to provide accurate estimate of weights of many components, such as electric motors.

Figure 5. A sample Pacelab APD Graphical User Interface

APD includes a library of computational methods that can be tapped for analyzing a specified Engineering Object or aircraft component. However, rapid and accurate estimation of the effects of multiple propellers on wing aerodynamics is beyond the current capabilities of the built-in methods. But this deficiency can be readily rectified due to the architectural flexibility of the software that allows users to alter individual methods in the computational library, simply replace one or more of them, or input externally generated aerodynamic data. In this study, aircraft aerodynamic data are generated outside of APD, and the required data are fed to APD as described in Section 2.3.

2.2 Aircraft Aerodynamics Estimation

The two primary means of estimating aircraft aerodynamic characteristics today are: wind tunnel testing and computational simulations. Wind tunnel testing is typically considered the most desirable. However, the associated expense of resources and long turnaround times make it unsuitable for conceptual-level trade studies or optimization studies. On the other hand, computational fluid dynamics (CFD) techniques are much better suited for simulating aircraft aerodynamics and to provide estimates of forces and moments, surface pressures, and flow fields. Computational simulations of aircraft configurations using CFD have become indispensable in modern day aircraft design and analysis [13].

At one end of the spectrum of CFD methods are the so-called high fidelity methods based on solving the Reynolds-averaged Navier-Stokes (RANS) equations. However, their high computational costs and long turnaround times restrict their effectiveness for conceptual or preliminary design exploration. At the other end are the so-called low fidelity methods based on solving the Prandtl-Glauert equation. The low fidelity methods are fast and inexpensive, hence well suited for early stages of design exploration. Vortex Lattice Methods (VLMs) belong to this category of CFD methods and are highly desirable for the application at hand.

2.2.1 OpenVSP and VSPAERO

Open Vehicle Sketch Pad or OpenVSP is an open-source parametric geometry tool developed by NASA for creation of three-dimensional (3D) models for conceptual design studies [14, 15]. OpenVSP bundles many analysis tools and provides output files that can connect to countless more. VSPAERO is one of the aerodynamic analysis tools that can be accessed through OpenVSP GUI. This tool solves potential flow equations using either vortex lattice method (VLM) or panel method. It is a robust, easy to use, cost-effective tool with fast turnaround time and proven ability to simulate the effect of single or multiple propellers on wing aerodynamics. A built-in actuator disk model, with Conway model to approximate the swirl effect, is particularly useful for propeller modeling. This propeller model requires the following inputs: propeller blade diameter, D; thrust coefficient, C_T; power coefficient, C_P; and rotational speed, n, in revolutions per minute (RPM). The propeller input parameters are defined as follows: $C_T = T/(\rho n^2 D^4)$; $C_P = P/(\rho n^3 D^5)$; and $n = \frac{a_\infty}{\pi D}\sqrt{M_{tip}^2 - M_\infty^2}$. Here ρ is atmospheric air density at the flight altitude; a_∞ is speed of sound, M_∞ is free-stream Mach number, and M_{tip} is the propeller tip Mach number which is typically kept below 0.7. A set of these propeller input parameters is generated for several altitudes and angles of attack, and used for VSPAERO analyses. Recent studies by many investigators including Shah [16], Sheridan *et al.* [17], and Polepeddi [18] confirm that VSPAERO predictions of aerodynamic parameters for a variety of aircraft configurations show reasonably good correlations with experimental data for angles of attack where the flow is expected to remain attached, i.e., no boundary layer separation.

2.3 VSPAERO-APD Coupling

For aircraft with multiple propellers, aerodynamic data from VSPAERO are integrated into APD as shown in Figure 6. The primary aerodynamic data are low-speed (take-off) and high-speed (cruise) drag polars that are input as tables which override the built-in methods for estimating aerodynamic data. Note that users have a choice to use either VSPAERO or the built-in methods.

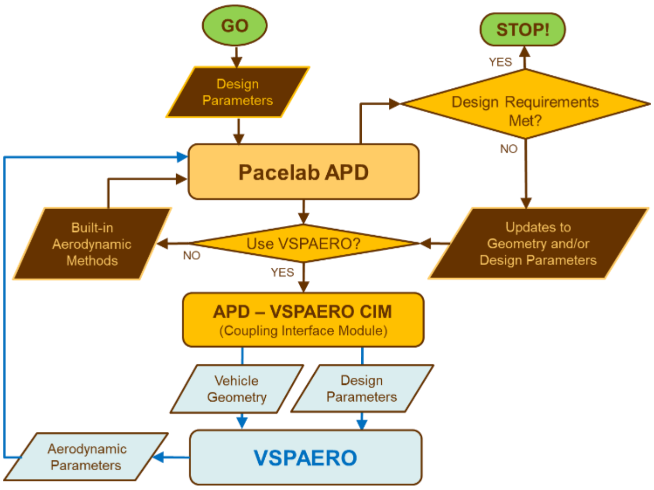

Figure 6. VSPAERO-Pacelab APD Coupling

This methodology was validated by comparing the results for the baseline ATR 72-500 (one of the aircraft in the Pacelab library) for two flight simulations with APD: (1) using built-in aerodynamic methods; and (2) using VSPAERO drag polars as inputs. For both simulations, APD used the mission profile shown in Fig. 4(b) along with the parameters shown in Table 1. Figure 7 shows a cruise drag polar at 0.45 Mach number and 25,000 ft. altitude that was generated using VSPAERO.

Table 1. Inputs for APD Simulations of Baseline ATR 72-500

PARAMETERS	VALUE
MTOW	22800 kg (50265 lbs)
MOEW	13500 kg (29762 lbs)
Max payload	7000 kg (15432 lbs)
Take-off speed (V2 min @ MTOW)	115 KCAS
Reference speed at landing	113 KIAS
Optimum climb speed	170 KCAS
Cruise speed	275 KTAS (510 kph)
Range with max pax (68)	772 nm

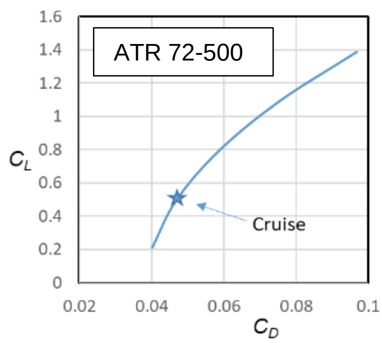

Figure 7. ATR 72-500 cruise drag polar using VSPAERO; 0.45 Mach number, 25,000 ft. altitude

The results showed that the estimated takeoff field length was within 1.5% (1333 m using the built-in methods vs. 1353 m using the present methodology), and estimated time to climb to 17000 ft. altitude within 6.5% (17.2 minutes using the built-in methods vs. 18.3 minutes using the present methodology).

2.4 Design Considerations

Incorporating a TEDiP system into the baseline ATR 72-500 presents a host of decisions that a designer needs to make. For example, (i) the number of gas turbines and their locations; (ii) the number and locations of propellers; and (iii) the type of generators and motors, i.e., alternating current (AC) or direct current (DC).

The first step in incorporating TEDiP into the baseline ATR 72-500 is to select a propulsion system architecture. Figure 8 depicts the architecture used in this study. The TEDiP architecture comprises four major components: turbine engine; generator; installed systems, and electric motor-propeller units. Pro/con decision matrices are used to select AC generators and DC motors [18].

Three TEDiP variants of the baseline twin-propeller ATR 72-500 aircraft are created: (1) four propellers (TEDiP-4P); (2) six propellers (TEDiP-6P); and (3) eight propellers (TEDiP-8P). Key design considerations that guide the creation of these variants are as follows:

- All TEDiP variants have two gas turbine engines as the primary source of power. A turbo-electric (TE) unit is composed of an engine and a generator. Each of the two inboard nacelles houses one of the two TE units. The decision to choose two units is motivated by the need to meet the one engine inoperative (OEI) regulatory constraint. Having two units should improve the chances of certifying the new designs.

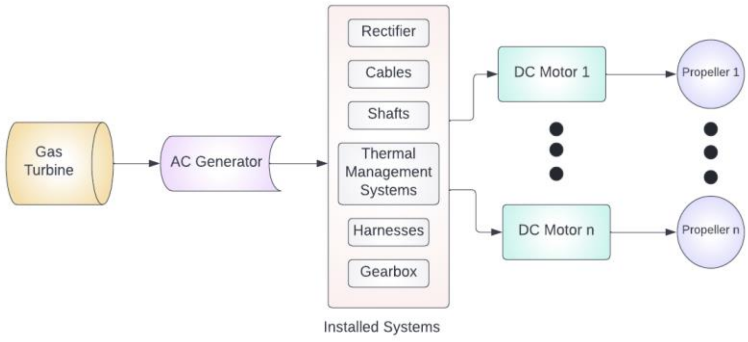

Figure 8. TEDiP system architecture

- To limit the design changes largely to the wing of the baseline, the inboard propellers on the TEDiP variants are identical to those on the baseline. Each of the additional propellers is half the diameter of the inboard ones. Table 2 shows the geometric parameters of the baseline ATR 72-500 and of the three TEDiP variants. Note that the propeller diameter in Table 2 is for each individual propeller. Figure 9 shows the three variants, and the propulsion units for each design are labeled from 1 to N where N is 4, 6 or 8. Note that the two inboard propellers operate throughout the flight mission. However, outboard propellers run for takeoff and climb only; they are turned off and folded back for the remainder of the flight.

Table 2. Geometric parameters of the baseline and three variants

PARAMETERS	BASELINE	TEDiP-4P	TEDiP-6P	TEDiP-8P
Wing chord (m)	2.33	2.33	2.33	2.33
Wing span (m)	27	27	27	27
Wing area (m^2)	61	61	61	61
Number of propellers	2	4	6	8
Propeller diameter (m)				
Inboard	3.93	3.93	3.93	3.93
Outboard	-	1.96	1.96	1.96

- Since the current version of APD requires each TE unit to power at least two propellers, one of the inboard nacelles houses one TE unit that powers two inboard propellers, and the other TE unit that powers the all of the outboard propellers is housed in the other inboard nacelle (on the opposite wing).
- Propulsion system is sized using an iterative procedure. Since incorporation of TEDiP system increases aircraft weight, the required SHP for a design variant is higher than that for the baseline. Therefore, an initial SHP value is chosen that is higher than that of the baseline, and the flight mission is simulated using APD. The SHP value is then iteratively adjusted to determine a minimum value required to successfully perform the prescribed mission while meeting the OEI constraint. Assuming propeller efficiency of 85% and using the estimated total required SHP, the total thrust for each variant is readily estimated.

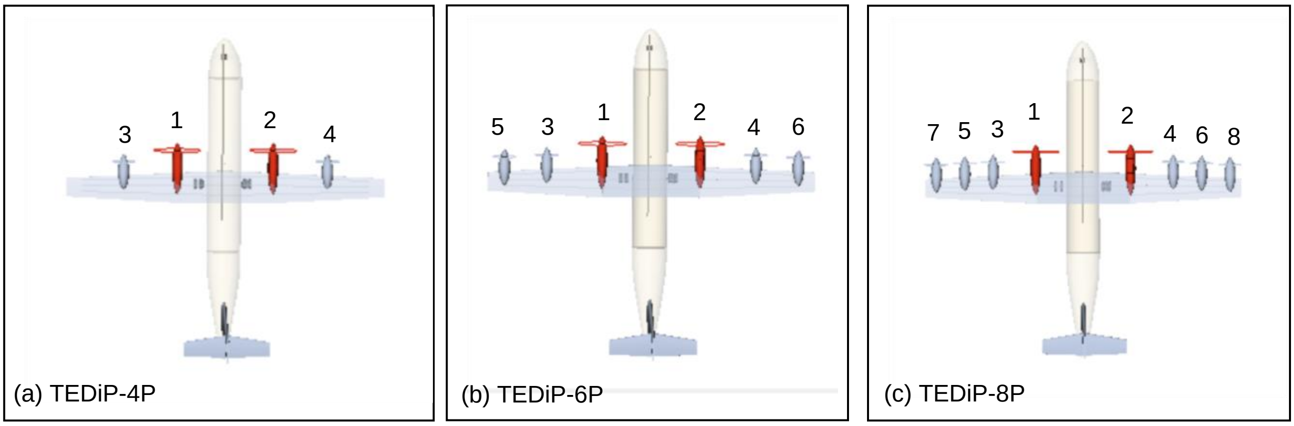

Figure 9. Three variants of ATR 72-500 with TEDiP systems

- Total thrust is distributed among the propellers based on their size while maintain the same disc loading for each [19]. (Disc loading is defined as thrust divided by swept or disc area of the propeller.) Hence, the larger inboard propellers produce higher thrust than the smaller outboard ones. In this study, an equivalent disc loading, $(T/A)_e$, is first calculated. Here T is the combined total thrust of all propellers (inboard plus outboard) and A is the sum of the disc areas of all propellers (inboard plus outboard). Thrust of individual propellers is then calculated to make sure that the disc loading of each propeller is $(T/A)_e$.
- To insure a fair comparison of the relative merits of all TEDiP variants, the flight performance of each variant is analyzed for a specified set of input parameters: payload (15,430 lbs.); range (772 nm); cruise speed (275 KTAS); and cruise altitude (23,000 ft.).
- Additional data inputs for simulations are: rated shaft horsepower (SHP) of the gas turbines; SHP and power densities of the electric motors; and efficiencies of all propulsion system components.
- It is assumed that motor power densities (MPDs) range for 6 to 12 kW/kg in the near term; 12 to 18 in the mid-term, and 18 to 24 in the far term [18].
- Outputs of APD include maximum takeoff weight (MTOW), operational empty weight (OEW), takeoff field length (TOFL), gas turbine and electric motor weights, and trip fuel.

3. Results and Discussion

One of the primary objectives of this study is to identify the potential benefits and/or penalties associated with the integration of TEDiP technology into a RTA. This is accomplished by comparing the results of the three TEDiP variants shown in Figure 9 with each other and with those of the baseline. For each case, MTOW, TOFL, and mission fuel are compared, and sensitivity to MPD variations in near, mid, and far term are computed. Results are presented in the following sections.

3.1 TEDiP-4P

The first design is a four-propeller TEDiP variant shown in Figure 9(a). It has two gas turbines with two generators. To successfully perform the mission, it takes one turbine engine rated at 6,200 SHP to power the two inboard propellers, labeled 1 and 2, and a second engine with 3,200 SHP to power the two outboard ones, labeled 3 and 4. The total required SHP is 9,400. Powering the two inboard propellers, 1 and 2, requires a 3,100 SHP electric motor each, and each of the two outboard ones, 3 and 4, requires a 1,600 SHP electric motor.

3.1.1 MTOW

As shown in Figure 10 and Table 3, an increase in MTOW compared to the baseline is observed due to the addition of TEDiP components. For MPD of 6 kW/kg (current motors), the weight increase is about 10%. If MPD increases to 24 kW/kg (far term), the weight increase is only about 5%.

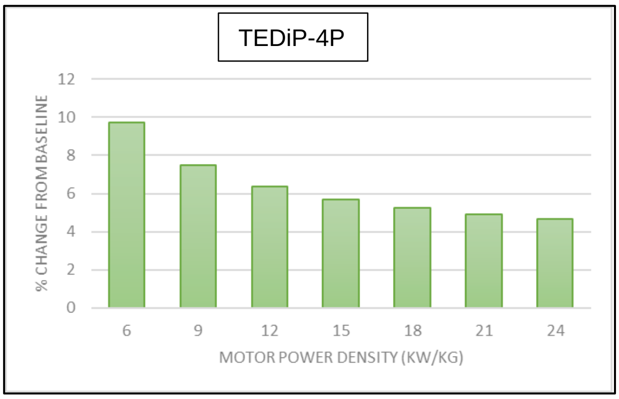

Figure 10. Change in MTOW (%) over baseline for TEDiP-4P with increasing motor power density

Table 3. Change in MTOW over baseline for TEDiP-4P with increasing motor power density

Motor Power Density (kW/kg)	MTOW (kg) TEDiP-4P	% Change from Baseline
6	25021	+9.7
9	24508	+7.5
12	24251	+6.4
15	24097	+5.7
18	23994	+5.2
21	23921	+4.9
24	23866	+4.7

3.1.2 TOFL

With increasing MPDs, the TOFL steadily decreases as shown in Figure 11 and Table 4. A decrease of about 14% is seen for the near term and of 21% for the far term. The decrease in TOFL is a direct result of the DiP technology which offers aerodynamic benefits through added lift from the interaction of multiple propellers with the wing.

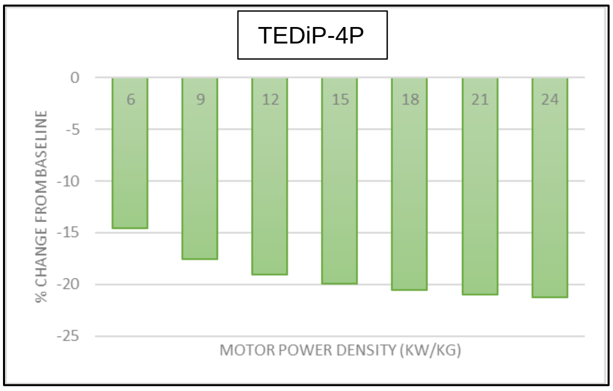

Figure 11. Change in TOFL (%) over baseline for TEDiP-4P with increasing motor power density

Table 4. Change in TOFL over baseline for TEDiP-4P with increasing motor power density

Motor Power Density (kW/kg)	TOFL (m) TEDiP-4P	% Change from Baseline
6	1156	-14.5
9	1115	-17.6
12	1095	-19.1
15	1083	-19.9
18	1975	-20.5
21	1069	-21
24	1065	-21.2

3.1.3 Trip Fuel

With increasing MPDs, the trip fuel also steadily decreases as shown in Figure 12 and Table 5. The decrease is between 8% and 10%.

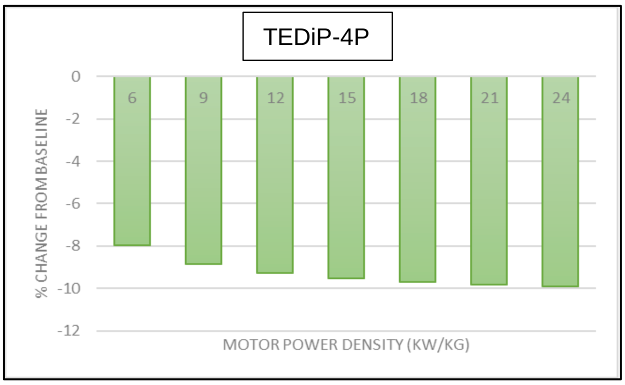

Figure 12. Change in trip fuel (%) over baseline for TEDiP-4P with increasing motor power density

Table 5. Change in trip fuel over baseline for TEDiP-4P with increasing motor power density

Motor Power Density (kW/kg)	Trip Fuel (kg) TEDiP-4P	% Change from Baseline
6	2312	-8
9	2290	-8.8
12	2279	-9.2
15	2273	-9.5
18	2268	-9.7
21	2265	-9.8
24	2263	-9.9

3.2 TEDiP-6P

The second design is a six-propeller TEDiP variant shown in Figure 9(b). It has two gas turbines with two generators. To successfully perform the mission, it takes one turbine engine rated at 6,700 SHP to power the two inboard propellers, labeled 1 and 2, and a second engine with 3,800 SHP to power the two outboard ones, labeled 3, 4, 5, and 6. The total power available is 10,500 SHP. Each of the two inboard propellers (1 and 2) is powered by a 3,350 SHP electric motor, and each of the four outboard ones requires a 950 SHP motor.

3.2.1 MTOW

As shown in Figure 13 and Table 6, an increase in MTOW compared to the baseline is observed due to the addition of TEDiP components. For MPD of 6 kW/kg for current motors, the weight increase is about 14%. If MPD increases to 24 kW/kg in the far term, the weight increase is only 8%.

3.2.2 TOFL

With increasing MPDs, the TOFL steadily decreases as shown in Figure 14 and Table 7. A decrease of about 20% is seen for the near term and of 26% in the far term. The decrease in TOFL is a direct result of the DiP technology which offers aerodynamic benefits through added lift from the interaction of multiple propellers with the wing.

3.2.3 Trip Fuel

With increasing MPDs, the trip fuel also steadily decreases as shown in Figure 15 and Table 8. The decrease is between 1.5% and 4%.

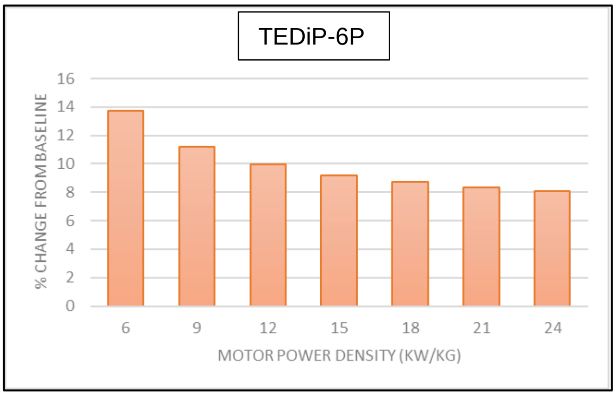

Figure 13. Change in MTOW (%) over baseline for TEDiP-6P with increasing motor power density

Table 6. Change in MTOW over baseline for TEDiP-6P with increasing motor power density

Motor Power Density (kW/kg)	TOFL (m) TEDiP-6P	% Change from Baseline
6	1079	-20.3
9	1040	-23.2
12	1020	-24.6
15	1008	-25.5
18	1001	-26
21	995	-26.4
24	991	-26.7

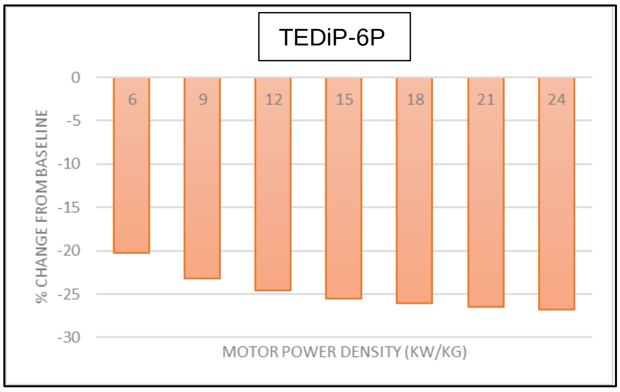

Figure 14. Change in TOFL (%) over baseline for TEDiP-6P with increasing motor power density

Table 7. Change in TOFL over baseline for TEDiP-6P with increasing motor power density

Motor Power Density (kW/kg)	TOFL (m) TEDiP-6P	% Change from Baseline
6	1079	-20.3
9	1040	-23.2
12	1020	-24.6
15	1008	-25.5
18	1001	-26
21	995	-26.4
24	991	-26.7

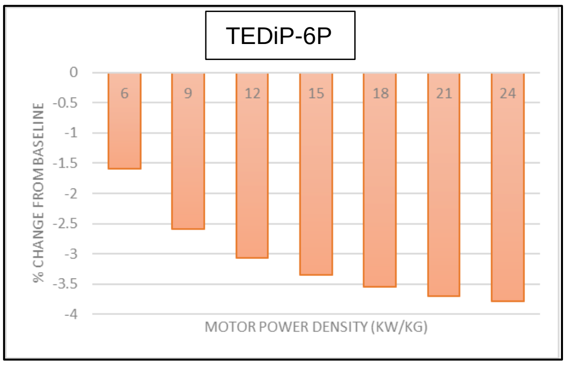

Figure 15. Change in trip fuel (%) over baseline for TEDiP-4P with increasing motor power density

Table 8. Change in trip fuel over baseline for TEDiP-6P with increasing motor power density

Motor Power Density (kW/kg)	Trip Fuel (kg) TEDiP-6P	% Change from Baseline
6	2472	-1.6
9	2447	-2.6
12	2435	-3.1
15	2428	-3.3
18	2423	-3.5
21	2419	-3.7
24	2417	-3.8

3.3 TEDiP-8P

The third design is an eight-propeller TEDiP variant shown in Figure 9(c). It has two gas turbines with two generators. To successfully perform the mission, it takes one turbine engine rated at 7,100 SHP to power the two inboard propellers, labeled 1 and 2, and a second engine with 4,500 SHP to power the two outboard ones, labeled 3 through 8. The total available SHP is 11,600. Each of the two inboard propellers (1 and 2) is powered by a 3,550 SHP electric motor, and each of the six outboard ones requires a 750 SHP motor.

3.3.1 MTOW

As shown in Figure 16 and Table 9, an increase in MTOW compared to the baseline is observed due to the addition of TEDiP components. For MPD of 6 kW/kg (current motors), the weight increase is about 17%. If MPD increases to 24 kW/kg (far term), the weight increase is only 11%.

3.3.2 TOFL

With increasing MPDs, the TOFL steadily decreases as shown in Figure 17 and Table 10. A decrease of about 24% is seen for the near term and of 30% in the far term. The decrease in TOFL is a direct result of the DiP technology which offers aerodynamic benefits through added lift from the interaction of multiple propellers with the wing.

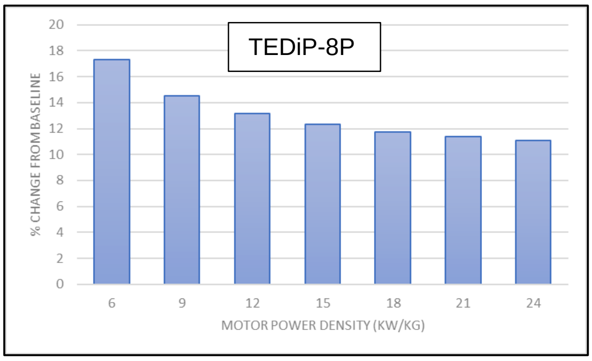

Figure 16. Change in MTOW (%) over baseline for TEDiP-8P with increasing motor power density

Table 9. Change in MTOW over baseline for TEDiP-8P with increasing motor power density

Motor Power Density (kW/kg)	MTOW (kg) TEDiP-8P	% Change from Baseline
6	26742	+17.3
9	26111	+14.5
12	25796	+13.1
15	25606	+12.3
18	25480	+11.8
21	25390	+11.4
24	25322	+11.1

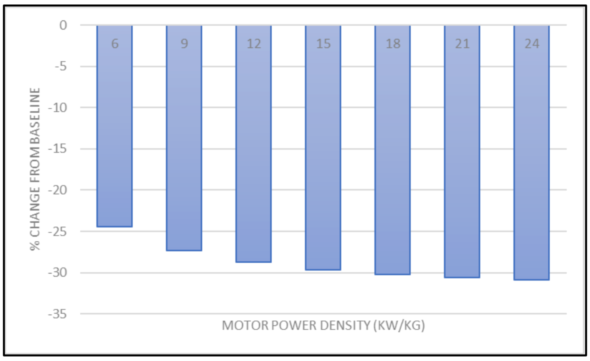

Figure 17. Change in TOFL (%) over baseline for TEDiP-8P with increasing motor power density

Table 10. Change in TOFL over baseline for TEDiP-8P with increasing motor power density

Motor Power Density (kW/kg)	TOFL (m) TEDiP-8P	% Change from Baseline
6	1023	-24.4
9	983	-27.3
12	964	-28.8
15	952	-29.6
18	945	-30.2
21	939	-30.6
24	935	-30.9

3.3.3 Trip Fuel

With increasing MPDs, the trip fuel steadily decreases as shown in Figure 18 and Table 11. However, for all motor densities, the trip fuel is higher than that of the baseline.

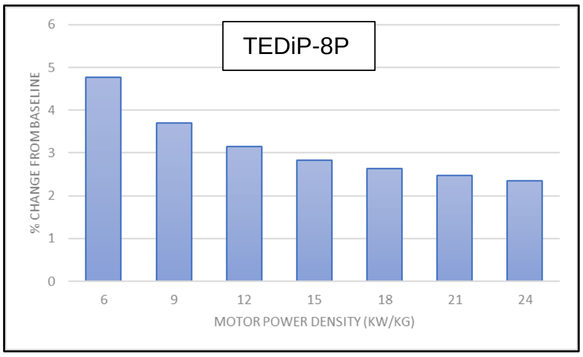

Figure 18. Change in trip fuel (%) over baseline for TEDiP-8P with increasing motor power density

Table 11. Change in trip fuel over baseline for TEDiP-8P with increasing motor power density

Motor Power Density (kW/kg)	Trip Fuel (kg) TEDiP-8P	% Change from Baseline
6	2632	+4.8
9	2605	+3.7
12	2591	+3.1
15	2583	+2.8
18	2578	+2.6
21	2574	+2.5
24	2571	+2.3

3.4 Comparative Assessment

In this section, two sets of results are presented. The first set shows sensitivity of MTOW, TOFL and trip fuel to variations in MPD ranging from the current 6 kW/kg to the far-term 24 kW/kg. The second compares masses of the power plant components of the three variants with each other and with that of the baseline for a MPD of 6 kW/kg.

3.4.1 Sensitivity to Motor Power Density

As shown in Figure 19, the takeoff weight of each variant is higher than that of the baseline regardless of the motor power density. However, this weight penalty is lowest for TEDiP-4P and highest for TEDiP-8P. For a MPD of 6 kW/kg, the weight penalty is nearly 10% for TEDiP-4P and about 17% for TEDiP-8P. As one would expect, additional components for the TEDiP architecture are the primary contributors to the weight increase.

The TOFL comparison, shown in Figure 20, indicates a reduction for all variants compared to the baseline. For a MPD of 6 kW/kg, the TOFL reduction is nearly 15% for TEDiP-4P, 20% for TEDiP-6P, and 24% for TEDiP-8P. The added lift due to the interaction of multiple propellers with the wing is the main contributor to TOFL reduction.

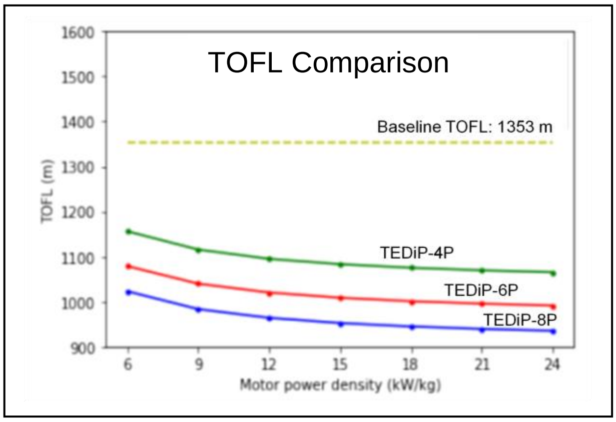

Figure 20. Change in TOFL for TEDiP variants with increasing motor power density

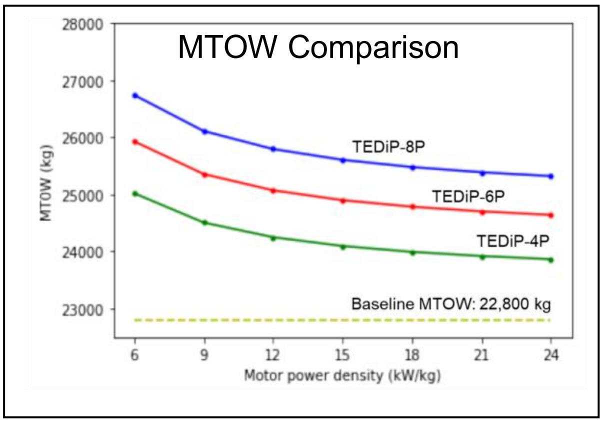

Figure 19. Change in MTOW for TEDiP variants with increasing motor power density

Figure 21 shows that both TEDiP-4P and TEDiP-6P have reduced trip fuel burn compared to the baseline. For a MPD of 6 kW/kg, the fuel burn is reduced by nearly 8% for TEDiP-4P and about 1.5% for TEDiP-6P. The amount of fuel burn is even lower as MPD increases over time. However, the TEDiP-8P variant burns more fuel than the baseline for all MPDs. This increased fuel burn may be attributed to increased weight due to a heavier power plant and higher parasite drag due to the additional motor-propeller-nacelle units.

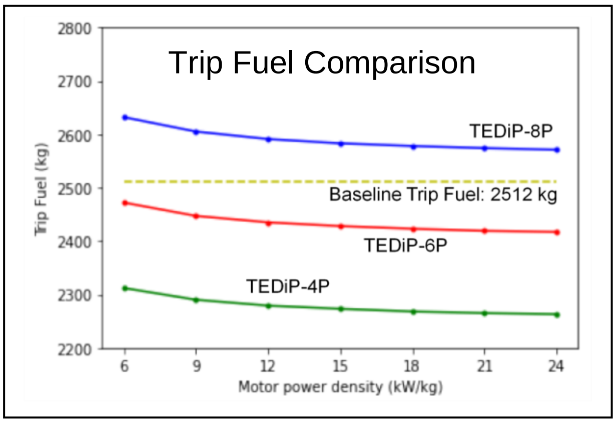

Figure 21. Change in trip fuel for TEDiP variants with increasing motor power density

APD results for three parameters, MTOW, TOFL, and trip fuel, are shown in Table 12. All are for the reference mission shown in Figure 4(b). Results are shown for two MPDs, one current (6 kW/kg) and the other midterm (15 kW/kg). Results for all three variants are compared with each other as well as with those of the baseline.

Table 12. Comparison of MTOW, TOFL, and Trip Fuel results for motor power densities of 6 kW/kg (current) and 15 kW/kg (near to midterm)

	Baseline	TEDiP-4P		TEDiP-6P		TEDiP-8P	
	NEAR TERM MOTOR POWER DENSITY of 6 kW/kg						
MTOW (kg)	22800	25021	9.7%	25930	13.7%	26742	17.3%
TOFL (m)	1353	1156	-14.5%	1079	-20.3%	1023	-24.4%
Trip Fuel (kg)	2512	2312	-8%	2472	-2%	2632	5%
	MID TERM MOTOR POWER DENSITYof 15 kW/kg						
MTOW (kg)	22800	24097	5.7%	24900	9.2%	25606	12.3%
TOFL (m)	1353	1156	-20%	1008	-25.5%	952	-29.6%
Trip Fuel (kg)	2512	2312	-10%	2428	-3.3%	2583	3%

3.4.2 Mass of Power Plant Components

Table 13 lists the power plant components required to incorporate a TEDiP architecture and compares their masses with the corresponding components of the baseline aircraft. It is evident that additional components increase the total power plant mass for all TEDiP variants. The largest increase comes from multiple electric motors required to drive the propellers. Generators required to produce electricity to power the electric motors, and an additional gas turbine that runs a generator to produce additional electric power for the outboard propellers needed to implement the DiP technology.

Table 13. Comparison of power plant component masses for TEDiP variants with the baseline for motor power density (MPD) of 6 kW/kg

COMPONENTS	BASELINE			TEDiP-4P			TEDiP-6P			TEDiP-8P		
	# of units	unit mass	total mass	# of units	unit mass	total mass	# of units	unit mass	total mass	# of units	unit mass	total mass
Engine Installation (kg)			**901**			**2823**			**3086**			**3347**
Gas turbines			902			1335			1462			1587
for two inboard propellers	2	451	902	1	841	841	1	895	895	1	937	937
for all outboard propellers	n/a			1	494	494	1	567	567	1	650	650
Electric Generators	n/a			2	160	320	2	160	320	2	160	320
Electric Motors	n/a					1168			1304			1440
for two inboard propellers	n/a			2	199	398	2	416	832	2	441	882
for all outboard propellers	n/a			2	385	770	4	118	472	6	93	558
Fuel Systems (kg)			**224**			**224**			**224**			**224**
Installed Systems (kg)			**1073**			**1579**			**1766**			**1941**
TOTAL (kg)			**2198**			**4626**			**5076**			**5512**

4. Concluding Remarks

In the present study, the authors integrated two novel technologies, viz., turbo-electric (TE) propulsion and distributed propulsion (DiP), into the baseline ATR 72-500 RTA. The overall objective was to assess any associated benefits and/or penalties in order to assess the role of these technologies in supporting the societal goal of sustainable flight in the near to midterm time frame. Three variants were created, each incorporating a TEDiP architecture: (1) four-propeller TEDiP-4P; (2) six-propeller TEDiP-6P; and (3) eight-propeller TEDiP-8P.

A few key takeaways from this study are:

- The estimated trip fuel burn is nearly 8% lower for TEDiP-4P and about 1.5% for TEDiP-6P compared to the baseline even with the current MPD of 6 kW/kg. These values increase to about 9% and 3% for MPD of 12 kW/kg. This finding suggests the potential benefit of TEDiP for reducing fuel consumption in the near-term.
- Distributed Propulsion (DiP) helps reduce the takeoff field length (TOFL) of the aircraft by as much as 20% in spite of an increase in the takeoff weight. This benefit is directly attributable to increased aerodynamic lift on the wing at takeoff conditions due to the interaction with multiple propellers.
- Ability of the TEDiP variants to takeoff from field lengths shorter than the baseline's 1353 m opens up access to more airports for operating ATR class RTA.
- Added components that comprise the power plant for TEDiP variants lead to weight penalty in terms of increased MTOW. However, anticipated improvements in electrical component technologies may help mitigate the level of this penalty in the future.

Since the authors conducted only a conceptual level study, the findings are not definitive but indicative of trends instead. Many areas need further exploration. Some of the recommendations for future work include:

- Investigate optimum location, size, and number of propellers to minimize trip fuel burn for a specified mission.
- Explore any aero-acoustic benefits for meeting stringent airport noise regulations.
- Expand the design space by relaxing a Pacelab APD constraint that requires one turboshaft engine to power two propellers. This may enable exploration of other options for TEDiP implementation.
- Investigate the effect of wing area reduction on further reducing fuel burn at the expense of sacrificing some of the benefits of reduced TOFL.
- Assess the accuracy of VSPAERO drag estimates, especially of the parasite drag.
- Develop methodology for accurate structural weight estimation that accounts for the effect of distributed propulsion.
- Explore ways of substantially reducing the turboelectric power plant weight, especially that of the installed systems including thermal management systems, power electronics, etc.

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6. Copyright Statement

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