Aircraft Design: Hybrid Electric Turboprop

Investigation of the Effect of Rising Fuel Prices on Aircraft Design

A Thesis Prospectus
In STS 4500
Presented to
The Faculty of the
School of Engineering and Applied Science
University of Virginia
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Aerospace Engineering

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October 27, 2022

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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INTRODUCTION

Amidst rising jet fuel prices, the need for climate-friendly, cost-effective solutions to air travel has expanded. According to Bouwer (2022), the price of jet fuel was around $4 a gallon in the United States in June 2022, which is an almost 215% increase since January 2021. Due to the Covid-19 pandemic air travel significantly decreased, leading oil refineries to shift their capacity away from jet fuel due to lower demand. In addition, Russia's invasion of Ukraine has drastically decreased international exports of both crude oil and refined products, pushing up the price. Even just an increase in price of a few cents can raise airline yearly operating costs by tens of millions of dollars (ibid). With global demand for jet fuel expected to double between 2019 and 2050, it is essential to find creative solutions to both the demand and price (Holladay et al., 2020). The price increase is not just reflected in operating costs. Consumers have seen an increase in ticket prices of 20% at the end of summer 2022 in comparison to 2019 (Pande, 2022). As a response, the aircraft design industry has started focusing on developing more fuel-efficient aircraft by both modifying existing technology and looking to new, disruptive technologies to find a solution.

An example of an advanced technology is the swirl recovery system. In this design, a set of swirling vanes is placed behind the propellor to offset the slipstream formed by the rotation of the propellor. This slipstream reduces the efficiency and thrust of the propellor, so by utilizing the vanes to reduce this effect, the overall aerodynamic efficiency increases, and less fuel is needed to yield the same amount of thrust (Li, et al., 2018). In addition to engine technologies, there are efforts to develop sustainable aviation fuel (SAF). The International Civil Aviation Organization (ICAO) defines SAF as alternative fuels that reduce greenhouse gas emissions, consider conservation regulations, and contribute to local social and economic development. At the moment, there are six ASTM International-approved variants of SAF fuel with blends varying from 10 to 50 percent hydrocarbons. Unfortunately, SAF is currently more expensive than Jet A fuel and most production sources do not have high enough yields to meet demand, hence the high price (Holladay et al., 2020).

Hybrid electric aircraft are more fuel and cost-efficient than traditional jet engines. Given the current state of technology and predicted future advancements, battery power is not sufficient enough to support an aircraft flying a range longer than a regional flight. The U.S. government is looking to prioritize battery development to get a specific energy of at least 500 Wh/kg by 2030 (DOE, 2021). This, however, is still minuscule in comparison to Jet A fuel at 12,000 Wh/kg (Clean Energy Institute, 2020). As a result, most of the hybrid electric aircraft in development are turboprops which are heavily favored within the industry for regional flight and are already more cost-effective than jet engines. A turboprop aircraft, see Figure 2, uses gas-turbine engines to rotate propellors whereas jet engine aircraft use a piston system (National Business Aviation Association, 2022). The engine is optimized to drive a propellor and is extremely efficient at lower flight speeds while burning less fuel per seat mile than a jet engine (Skybrary, 2021). At present time, if all regional jets were replaced by turboprops the regional jet industry would see a 28% decrease in CO2 emissions in the United States and a 33% decrease in Europe (ATR, 2022). The biggest design challenges with hybrid electric aircraft are minimizing battery weight while maintaining speed and range and properly integrating the electric system into the aircraft.

Figure 2. The Bombardier Dash 8, one of the most common turboprops currently on the market. (Image source: Aerospace Technology, 2022)

This prospectus will focus on the design of a hybrid electric regional turboprop ready for an entry-into-service date of 2035 and look at the impact of rising fuel prices on aircraft design through a technological momentum framework.

TECHNICAL TOPIC

This capstone project will focus on designing a hybrid electric regional turboprop aircraft ready for an entry-into-service (EIS) date of 2035 with the final design being entered into the American Institute of Aeronautics and Astronautics (AIAA) design competition. The project is part of the Aircraft Design course in the Mechanical and Aerospace Engineering Department at the University of Virginia. The design team consists of nine total members who will collaborate to build and integrate all facets of the aircraft using developing hybrid electric technologies. The team leaders are Robert Taylor and Christian Prestegard and the other members are Danny Lattari, Kazi Nafis, Kyle Hunter, Michael Richwine, Nathan Vu, Vincent Fimiani, and myself. The Request for Proposal (RFP) on the AIAA website gives mandatory and tradable requirements for designs submitted to the competition as well as an outline for the final report. The hybrid electric turboprop must seat 50 people and have a range of 1000 nautical miles with both passengers and cargo. The engines used in the aircraft must reflect a technology level that could be certified by 2034 so that the aircraft meets the required EIS date of 2035. Additional requirements are given for cruise speed, seat width, cross-section, wing span, performance, certifications, and payload. The main goals are to reduce block fuel by at least 20% and CO2, NOX, and soot emissions in comparison to current turboprops. The report will present the final performance capabilities and operating limits and must include proper diagrams, geometries, cost predictions, and other important aerodynamic data (AIAA, n.d.).

Regional turboprop aircraft typically provide more runway flexibility, lower carbon emissions, and increased cost-efficiency compared to jet engines (Syal, 2020). These aircraft typically seat anywhere from 20-90 passengers for commercial flights and are also commonly used in the air cargo market. There is a multitude of challenges facing the design of hybrid electric regional turboprop aircraft for an EOS of 2035. Environmentally speaking, a larger percentage of electrical power compared to jet fuel is favored to lower the use of fossil fuels. However, this requires a precise combination of electric aerial propulsion (EAP) technologies, see an example of an EAP configuration in Figure 3, as the additional components required for hybrid electric systems increase the payload, resulting in a higher total energy requirement for flight. Managing the total weight of the aircraft while meeting the requirements set out by AIAA will be one of the most demanding aspects of the project.

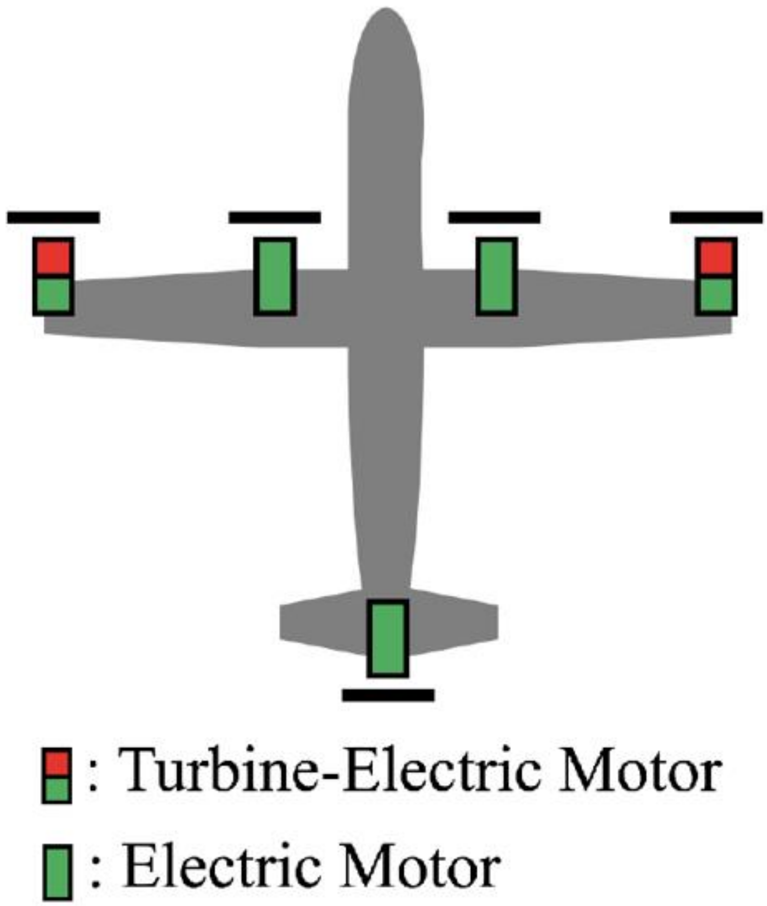

Figure 3. Propulsor configuration on the NASA PEGASUS. (Image source: Capristan & Welstead, 2018)

The design team has chosen to model the aircraft after the NASA PEGASUS, the NASA X-57 Maxwell, and the Bombardier Dash 8 (See Figures 4 and 5). Both NASA aircraft are parallel hybrid electric systems where fuel is used to power the turboshaft engine and batteries to power an electric motor while both are used simultaneously to power the drive train coupled to the propellors (Hung & Gonzalez, 2012). This means batteries are used to supplement the power from the engine throughout the flight. The power split between the two can be adjusted for different stages such as takeoff, climb, and cruise. The Dash 8 is the closest current turboprop design to the requirements laid out in the RFP. Multiple design proposals combine these aircraft and the team is currently working to figure out which one is both the most feasible and able to meet as many requirements as possible.

Figure 4. Artist rendering of the NASA X-57 Maxwell (Image source: NASA, 2022).

Figure 5. Artist rendering of the NASA PEGASUS (Image source: Blaesser, 2019).

STS TOPIC

Aircraft companies have been aiming to expand both passenger and cargo capacity to increase profits from both the commercial flight and air cargo markets. Due to the rise in fuel prices, smaller regional turboprops are no longer economically advantageous, so future fleet growth will be primarily focused on the integration of larger aircraft. High-volume aircraft (over 50 seats) are less maneuverable on short, rugged, unpaved, or steep runways and therefore unable to maintain connectivity with airports possessing those conditions. Regional turboprops capable of operating given tough runway conditions, such as the ATR 42-600S, enable access to several hundred more airports globally (ATR, 2022). If hybrid-electric technology could reduce fuel costs to the point where smaller aircraft could operate at the same economic level as larger aircraft, airlines would be encouraged to include more diverse routes and retain connections with remote areas. The people living in those areas would benefit from the opportunity to travel as well as the ability to ship more of their domestic products.

Hughes' (1987) article defines technological systems and analyzes their evolution over time through different themes. Technological system artifacts consist of physical technology, organizations, legislature, and natural resources while components are the human aspects such as engineers and manufacturers. Hughes argues that if a sector of a system changes, the others will adapt to compensate for this change. Radical inventions do not contribute to the growth of technological systems as they set precedent for a new technological system to form, but typically need assistance from a larger organization to give them momentum. However, not all large companies or organizations have the freedom to take on radical inventions. Depending on the bureaucratic environment and potential regulations some companies are "inert" and incredibly resistant to changes in momentum. Technological style refers to the concept that different methods or implementations can still lead to the same result. Competition refers to different components of a system recognizing a problem and searching for the most economically beneficial solution. The momentum of a technological system is directly related to its rate of growth. A system with artifacts and components supporting it as well as meeting the themes described by Hughes, such as invention and innovation, is more likely to have growth in the future (ibid).

Technological momentum is a good way to analyze how the increasing price of jet fuel has driven change in other facets of the aviation system through the themes described by Hughes. Particularly concerning my technical project, hybrid electric aircraft are a radical invention gaining momentum through the support of large organizations such as NASA, Boeing, and ATR. The different electric aircraft propulsion (EAP) architectures and methods of integration show technological style as they can achieve the same results, however, the designs are diverse. There are several hybrid electric architectures: series, parallel, turboelectric, and mild hybrid and these can be integrated into various parts of the plane such as the wings, fuselage, or tail. Organizations are not only competing to get the technology out fast but also to find the most cost-effective option to increase their profits.

RESEARCH QUESTION AND METHODS

The research question I will be answering is how have rising jet fuel prices influenced aircraft design. This directly relates to my technical project as we are designing a hybrid electric aircraft which is a new technology aimed at reducing fuel costs and emissions. I will be looking into how different stakeholders are affected by the price increase and how they plan to adapt in the future. This will include manufacturers, consumers, commercial airlines, and gas companies.

The primary component of the aviation industry technological system I plan to analyze is aircraft manufacturers such as Boeing, AirBus, and ATR. Ideally, I will interview someone developing jet engine aircraft as well as someone developing a hybrid electric aircraft. I would like to ask about promising emerging technologies to reduce fuel consumption, any major design changes they've made on new aircraft, and if they think the price of jet fuel will continue to rise and what the industry needs to do to adapt. Specifically, regarding a hybrid electric aircraft, I would like to ask whether they think this technology is feasible for large-scale commercial flight and how many years in the future would they predict it would be possible. To end each interview, I plan to ask if they have any suggestions on other sources I can use or anyone else I could interview on this topic.

Secondary sources I will be using include relevant legal rulings on carbon emissions, EPA reports on aviation standards in the US, and EU aviation standards. Both current and future rulings on emissions reduction provide a metric for how much improvement in fuel efficiency and emissions needs to happen in the aviation industry. I plan to analyze these sources before conducting interviews to get a solid background and be able to reference specific requirements when asking about design changes.

CONCLUSION

The final design from the technical project will be a hybrid electric regional turboprop aircraft ready for an EIS of 2035. Relevant figures and dimensions will be detailed in a paper which will be submitted to the AIAA's 2022-2023 design competition. The paper will also justify all design choices made and detail which requirements were met. As the aviation industry moves towards more environmentally friendly, cost-efficient options, hybrid electric architectures will become more prevalent. There are already hybrid electric and fully electric cars, and now that technology is expanding to aerial vehicles.

Another paper will be written on the impact of rising fuel prices on aircraft design through the technological momentum framework. It will analyze the impact of rising fuel prices on different components of the aviation industry system including manufacturers and consumers.

In addition, the paper will draw conclusions about where aircraft design is heading in the future utilizing direct evidence collected from interviews and relevant carbon emissions reduction goals.

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