Return of Propellers: Advancing Towards Sustainable Aviation

Daamanjyot Barara
Flight Performance and Propulsion, Department of Aerospace Engineering Delft University of Technology Delft, The Netherlands Flight Performance and Propulsion, Department of Aerospace Engineering, Delft University of Technology, Delft The Netherlands
daamanbarara@gmail.com

Abstract— In the pursuit of sustainability, the aviation industry is investing and adopting new technologies while improving the existing ones. The challenge of making aviation sustainable is compounded by the growing passenger demand. To cater to the increasing demand, propellers have gained traction in recent times given its exceptional propulsive efficiency. Historically, advancements in propeller technology have been instrumental in improving performance and reducing noise, paving the way for their application in modern sustainable aviation. Today, these past developments are being leveraged to design disruptive technologies, such as advanced propellers capable of matching the performance of current turbofan engines. Moreover, propellers are becoming central to the role of electric and hybrid-electric propulsion systems, where their efficiency aligns well with the limited energy density of current batteries. Light is further shed on the development of new open-rotor engines offering up to 20% fuel savings compared to that of modern turbofan engines. Despite such advancements in propeller technology, challenges persist in terms of propeller aeroacoustics and airframe integration.

Keywords: Propeller, Propfan, Open-Rotor, Sustainable aviation, Propulsive efficiency, Turboprop aircrafts, Advanced turboprop project, Transonic regime

I. INTRODUCTION

SINCE the inception of aircraft, the aviation industry has been a key driver of global connectivity, enabling economic growth and cultural exchanges. There was a consistent growth in the number of global passengers before the pandemic, and despite a lull period during the pandemic, there has been a strong rebound. The International Air Transport Association (IATA) predicts that this figure will reach 5.6 billion by 2030 [1]. As the passenger demand continues to rise, the aviation industry continues to contribute 2.5% of world's carbon emissions. To keep aviation's impact on environment in check, the International Civil Aviation Organization (ICAO) has set a goal of achieving net-zero CO_2 emissions by 2050. Therefore ICAO is prompting aircraft manufacturers to explore sustainable aircraft options to meet the demands while adhering to environmental regulations.

The pursuit for sustainable aviation spans from researching alternative power sources for aircraft to developing unconventional airframe designs. Several studies on alternative energy sources, such as all-electric and hybrid-electric architectures, highlight propellers as a propulsion system due to their exceptional aerodynamic efficiency [2, 3]. For the same reason, propellers are being incorporated into novel airframe design concepts, such as boundary-layer ingestion and distributed propulsion, where the interaction between the airframe and propellers is leveraged to enhance aero-propulsive efficiency [4, 5]. Similarly, the propellers are becoming central to the designs of various electric vertical take-off and landing (eVTOL) aircraft.

While propellers are increasingly being incorporated into novel technologies, they are already effectively catering to the regional market. Their ability to generate significant thrust at low speeds allows for shorter takeoff and landing distances, as well as quicker climb times, making them ideal for airports with shorter runways. This capability has enabled airline operators to open new routes to smaller destinations, enhancing regional connectivity. As a result, turboprop aircraft remain widely used for short-distance regional transport in civil aviation. But, with further growth in the passenger numbers, the consequent increase in number of regional flights powered by propellers is obvious.

Amid the growing interest in propeller technology, it is becoming clear that propellers could play a significant role in the future of sustainable aviation. Advancements in propeller technology has made it a key candidate for the industry's solution to sustainable travel, due to its low environmental impact while maintaining high efficiency.

II. THE PROPELLER

The propeller was the first propulsor to enable the first-ever heavier-than-air powered flight, achieved by the Wright brothers in 1903. Similar to the principle of a wing, the Wright brothers recognized the propeller as a rotating wing that moved in a helical path producing lift in the forward direction, which we refer to as thrust. In this work, the term 'propeller' is used to refer to a type of aircraft propulsor that uses one or more unducted fans, regardless of the range of cruise speeds at which it operates.

During the pioneer era of aviation up to the 1950s, extensive research on propellers led to significant advancements in propeller technology, enabling propeller-powered flights to achieve cruise speeds of up to Mach 0.6. However, with the introduction of turbojets and turbofans, which promised efficient cruise flights at higher speeds ranging from Mach 0.6 to 0.85, the use of propellers declined. This decline was primarily due to the inability of the propellers at the time to overcome compressibility losses experienced at high Mach numbers that caused increased drag and noise. Additionally, the propellers with a reliable structural stability at the time would break or suffer damage at these high speeds. Therefore, even though propellers offered higher propulsive efficiency up to Mach 0.6, they were outperformed by the greater speed, longer range, and quieter cabins provided by turbojets and turbofans. The fuel prices at the time wasn’t a concern as they were priced low.

It wasn’t until the early 1970s when the oil embargo placed by the Organization of Petroleum Exporting Countries (OPEC), fuel prices became a concern worldwide. This energy crisis was a catalyst for NASA to explore viable fuel-saving concepts. This served as an impetus to research high-speed propeller technology through NASA’s Advanced Turboprop Project (ATP) [6]. Based on the experience gained in the 1950s, researchers were well aware of the potential of propeller to provide high propulsive efficiency at high subsonic and transonic speeds, provided the compressibility effects, noise, and vibrations could be addressed. materials, aerodynamics, and computational modelling, the NASA Advanced Turboprop Project (ATP) aimed to develop propellers capable of operating efficiently at high speeds while reducing fuel consumption. Initial research demonstrated that when a highly-loaded, multi-blade, swept propeller—referred to as a propfan—was combined with the latest engine technology, it could achieve fuel savings of up to 50% compared to an equivalent turbofan engine operating at the same speed and altitude [7]. As can be inferred from Fig. 2, propfans achieved higher propulsive efficiency than turbojets and turbofans for the given range of high-speed during cruise flight, i.e., M = 0.7 to M = 0.8.

The propfans were visibly different from the conventional propellers. Unlike conventional propellers with a smaller number of straight blades, propfans often had multiple thin, highly swept blades designed to operate efficiently at transonic speeds. Sweeping the blade tip addressed two critical issues – compressibility effects at transonic Mach numbers and propeller noise. First, sweeping the blade reduced the effective Mach number at the blade tips, delaying the onset of shock waves and compressibility effects. Combined with the use of thin airfoil sections, this design minimized drag and enabled propellers to perform efficiently in the transonic regime. Secondly, the swept blade design altered the noise signals emitted from different portions of the blade, contributing to noise reduction.

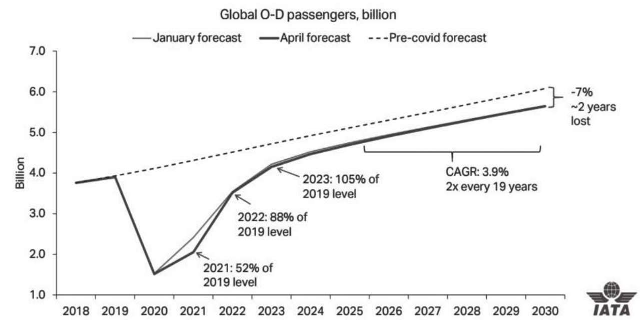

Figure 1. Forecast of the number of global passengers in aviation. [1]

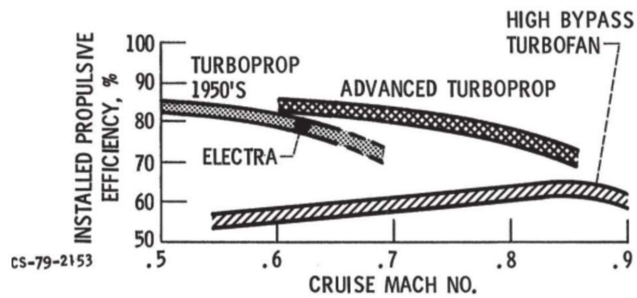

Figure 2. Installed propulsive efficiency trends in cruise. [6]

Another concept involves propellers with aft rotor or stator, where the propeller›s efficiency is enhanced by adding an additional row of rotating propellers or stators. One example of such a propeller with counter-rotating second stage is shown in Fig 4. This secondary row reduces swirl losses in the wake of the forward blade row, thus improving overall aerodynamic performance. So, there was a consistent effort to achieve high propulsive efficiency at high speeds. Even though the propellers developed under the ATP were a promising concept, the reduction in oil prices at the end of the 1980s halted the research and shifted the focus of commercial airliners back to turbofans.

ANSWER TOWARDS SUSTAINABLE FLyINg – PROPELLERS ?

Different air-breathing propulsion systems are designed based on the following two equations:

$$T = (dm/dt)\,(v_e - v_o) \quad (1)$$

$$\text{Efficiency, } n_p = 2/\,[1 + (v_e / v_o)\,] \quad (2)$$

Equation (1) relates the thrust force produced by the propulsor as a product of the mass flow rate ingested by the propulsor, $\dot{m}$, and the difference between the exit velocity, v_e and the inlet velocity v_o

Equation (2) relates the propulsive efficiency to the ratio of exit and inlet velocity. Based on first equation, there are two ways

$\dot{m}$

to produce thrust. One way is to add a large increment to the exit velocity to a small amount of mass flow. Based on the first equation, there are two ways to produce thrust. The other way is to add a smaller increment to the exit velocity but apply it to a much larger mass flow. The turbojets and ramjets rely on the former approach, making them suitable for high-speed flight. Turbojets and ramjets rely on the former approach, making them suitable for high-speed flight. In contrast, turbofans and propellers leverage the latter approach, which, as shown in (2), leads to higher propulsive efficiency.

Hence, accelerating a large amount of air by a small increment is beneficial. This principle was a key concept behind the design of turbofans and led to the introduction of the bypass ratio (BPR), which is a measure of how much air bypasses the engine core compared to the air passing through it. Higher propulsive efficiency is achieved by increasing the BPR. Additionally, this also lowers the noise produced by the ducted engines. As can be inferred from the Fig. 5, there has been a consistent attempt to increase the BPR. In pursuit of improving fuel efficiency and inherently lowering emissions, turbofan engines have grown larger in size to ingest more mass flow.

However, this comes with an increase in the size of the surrounding nacelle to accommodate larger fan, which makes the engine heavier and increases drag. Due to these physical limitations of an aircraft, increasing the size of a turbofan becomes unviable. On the other hand, removing the nacelle and increasing the blade diameter, as with propellers, allows for ingesting a larger amount of mass flow, which immensely increases the BPR, as shown in Fig. 6. This results in lower fuel consumption at a given flight speed.

With the increasing demand for air travel in the coming years, and the need to meet this demand while adhering to stringent emission regulations set by regulatory authorities, propellers are making a comeback. In the context of high-cruise flight, CFM International is currently testing the open rotor concept through their RISE program, which includes stator vanes positioned aft of the main row of propellers [9]. CFM International claims that the open rotor fan concept can reduce fuel burn and emissions by 20% compared to the latest generation of turbofans. The engine is also compatible with sustainable aviation fuel (SAF) and hydrogen, aiming to further reduce CO2 emissions. CFM has proposed various aircraft configurations in which the open rotor can be installed as shown in Fig. 8. This has attracted also attracted Airbus, seeing the RISE engine as one of the potential candidates for propulsor on their new single-aisle aircraft.

Given the impressive propulsive efficiency of propellers, they have become a prominent choice for full-electric and hybrid-powered aircraft. Due to the limitations of the current state-of-the-art batteries, particularly in terms of their energy density and weight, they are better suited to power aircraft using propellers.

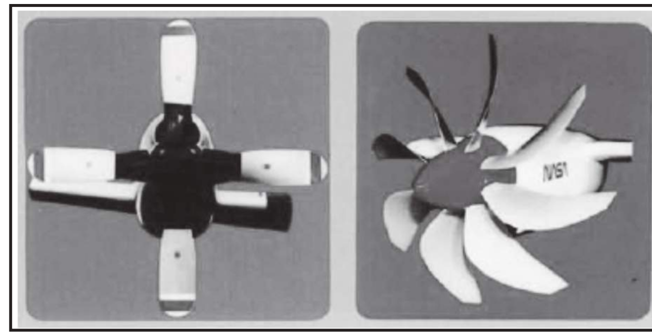

Figure 3. Comparison of the conventional propeller (left) and propfan (right) from NASA ATP. [7]

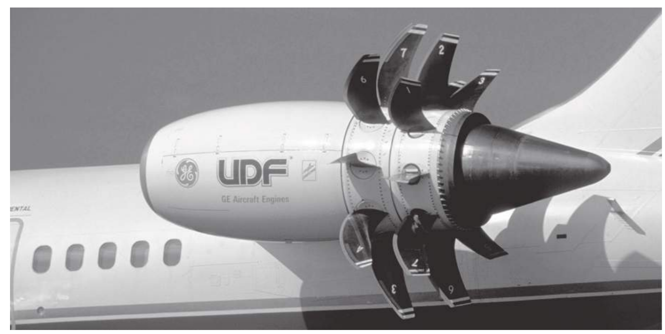

Figure 4. GE-36 Unducted Fan (UDF). Image: Wikipedia

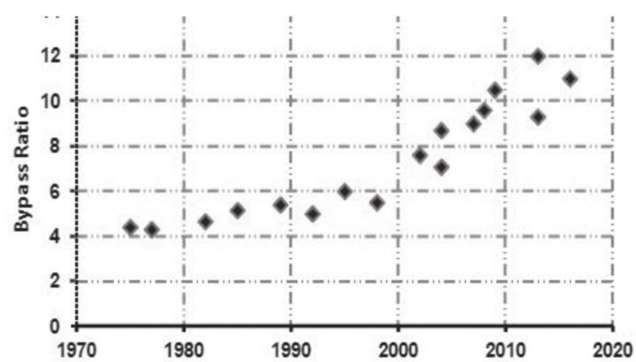

Figure 5. Development of bypass ratio (BPR). [8]

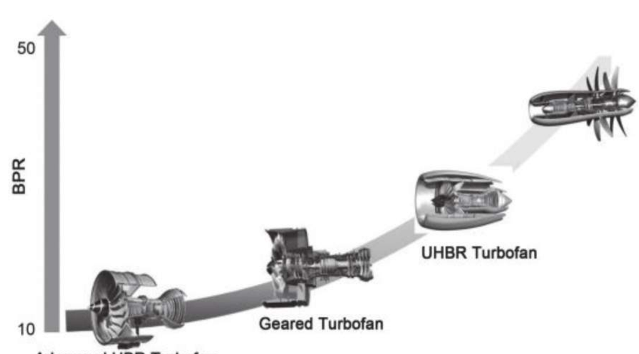

Figure 6. Variation of bypass ratio across technologies. [8]

Figure 7. CFM RISE Engine. [9]

Figure 8. Various aircraft configurations installed with open rotor. [9]

Figure 9. Render of Heart Aerospace's hybrid-electric aircraft ES-30. Image link : http://heartaerospace.com/es-30/

Figure 7. CFM RISE Engine. [9]

When paired with electric motors, propellers represent the most efficient propulsion option for regional flights. This efficiency has also driven their widespread adoption by numerous eVTOL companies.

IV. CHALLENgES TO WIDESPREAD ADOPTION

In principle, propellers are an attractive option for meeting the need for reduced emissions and improved fuel efficiency; however, they are not free from challenges which could hinder the large-scale introduction of propeller-driven aircraft. Some of the key challenges are stated here:

Noise – Due to the absence of a duct around the propeller, there is no noise attenuation, and the noise is directly emitted towards the surrounding environment and observers. Several studies have been conducted to assess the impact of propeller noise on the comfort of passengers and residents living close to airports. The effects include disturbance in sleep, concentration interference while performing tasks, and psychological effects. Noise has always been a challenge in the large-scale implementation of propellers, and much of the research during the 1980s focused on propeller noise. As noise regulations become even stricter, addressing the noise challenge is increasingly important for airliners to accept propellers. This is often cited as a major barrier to the introduction of eVTOL aircraft, which are typically powered by propellers and operate at low altitudes.

Passenger acceptance – Community acceptance is closely tied to the preceding issue of propeller noise, along with the vibration induced by propellers. In a study on passenger comfort in turboprop aircraft, the results showed that 91% of passengers were affected by noise, while 63% were affected by vibration []. This highlights how unpleasant the passenger experience can be onboard a propeller-powered aircraft. Another concern related to propellers is the blade-out scenario. Although current turboprops are certified only after proving their safety in such scenarios, it remains a concern for a large number of passengers flying on propeller-driven aircraft.

Airframe integration – Integration of the propellers into the airframe is critical to its performance. Due to the close coupling between the propeller and the airframe, deviations from the operating point can significantly impact the aero-propulsive performance. This is especially critical when propellers are installed in unconventional configurations, such as boundary-layer ingestion, distributed propulsion, or aft-mounted pusher configurations.

V. CONCLUSION

The aviation industry has a pressing need to meet the increasing passenger demand while meeting the sustainability goals. The propeller's impressive propulsive efficiency makes it a viable option for incorporation in the aircraft of the future. This is especially true where unconventional aircraft configurations are being explored by installing propellers in close proximity to the airframe to leverage its performance and enhance the aero-propulsive efficiency of the aircraft. Likewise, propellers are the 'go-to' propulsors for electric and hybrid-electric aircraft given the limited energy density of the current state-of-the-art batteries. Currently, propeller-driven aircraft are widely used in the regional market where they fly low and slow. But, with the pressing need to meet the demand for long-range travel of the future, they are widely being researched to fly higher and faster. Past research in propeller technology has already demonstrated that propellers can achieve installed propulsive efficiency of 80% at cruise Mach of 0.7-0.8. Combining new engine technology with the outcomes of the propeller research from the 1980's, the new open-rotor concept could provide a fuel-savings and a reduction in emissions of up to 20% compared to modern turbofan engines at the same speed and altitude. Even with such impressive performance, the widespread use of propellers is faced with hurdles mainly due to the issues arising from propeller acoustic and integration with the airframe.

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Daamanjyot Barara (b. 10 Feb 1996) is currently working as a Researcher at the Department of Flight Performance and Propulsion in the Faculty of Aerospace Engineering of Delft University of Technology, The Netherlands.

His current research work focuses on designing propeller blades while accounting for interference effects during installation on unconventional aircraft designs.

This involves developing innovative methodologies to optimize blade performance in the presence of complex flow interactions, ensuring enhanced efficiency and noise reduction for modern sustainable aviation applications. He holds a B.Tech degree in Mechanical Engineering from SRM University, graduating in 2018. He then completed his M.Sc in Aerospace Engineering at Delft University of Technology, The Netherlands, in 2022. Over the years, Daamanjyot's work has focused on utilizing computational fluid dynamics (CFD) combined with multidisciplinary design optimization (MDO) in the fields of air-breathing and rocket engines.