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Aircraft Propellers, an Outdated Innovation?

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Abstract

The race for speed ruled the early Jet Age on aviation. Aircraft manufacturers chased faster and faster planes in a fight for pride and capability. In the early 1970s, dreamed that the future would be supersonic, but fuel economy and not acceptable noise levels made that era never came. After the 1973 first oil crisis, the paradigm changed. The average cruise speed on newly developed aircraft started to decrease in exchange for improvements in many other performance parameters. At the same pace, the airliner's powerplants are evolving to look more like a ducted turboprop, and less like a pure jet engine as the pursuit for the higher bypass ratios continues. However, since the birth of jet aircraft, the propeller-driven plane lost its dominant place in the market. Associated with the idea of going back to propeller-driven airplanes, and what it represented in terms of modernity and security, it started a propeller avoidance phenomenon on the travelers and thus on the airlines. Today, even with the modest research effort since the 1980s, the advanced propellers are getting closer efficiencies to the jet-powered engines at their contemporary typical cruise speeds. This paper gives a brief overview of the performance trends in aviation since the last century. Comparison examples between aircraft designed on different paradigms are presented. The use of propellers as a reborn propulsive device is discussed.

Keywords: Propeller, Aircraft, Turboprop, Flight efficiency, Flight speed

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1. Introduction

The propeller is a device that converts the rotary power of an engine or motor into a thrust force that pushes the vehicle to which it is attached. Comprised by one or more radial airfoil- section blades rotating about an axis, the propeller acts as a rotating wing.

Aircraft propellers first emerged at the end of the 18th century; however, this study only discusses its history from the 20th and beyond. See Ref. [1], [2] for a historical review from the preceding decades.

By the end of the 19th century, a feeling of disbelief on the heavier-than-air, manned flight was present [3]. However, the first controlled, powered flight, starred by the Wright Brothers in 1903, marked the turn of a page of skepticism concerning the heavier-than-air, manned, flight. This remarkable achievement brought an increased excitement around the aviation community, and on the period 1905-1910, there has been an impressive growth in the number of filled patents [4].

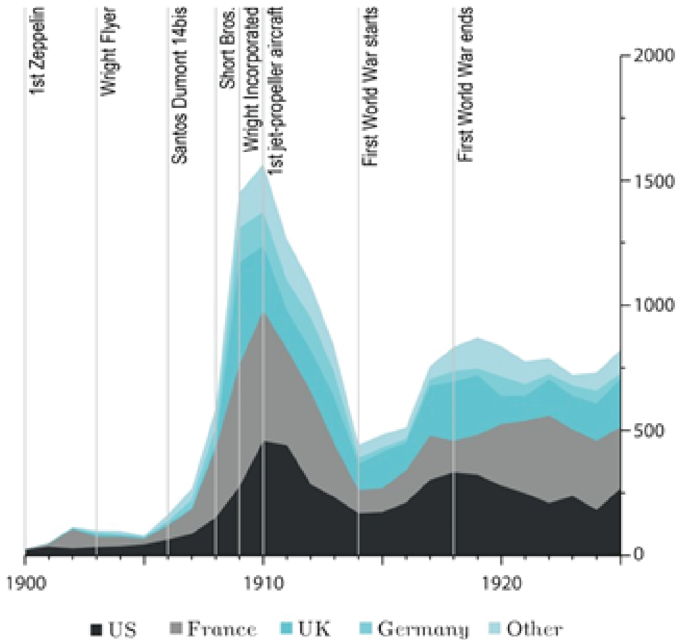

Figure 1: First patent filings by origin, 1900-1925. Between 1900 and 1970, patent filings relating to aviation tended to concentrate in the US, France, Germany, and the UK. Source: adapted from [4].

This pre-WWI period was also responsible for a transition from individuals as hobbyists and enthusiasts, motivated by curiosity, pride, and fame, to institutions and governments acknowledging the airplanes as a strategic weapon to win wars. By the end of WWI, from the 1920s up to the 1930s, designers, engineers, and inventors established new, active, and venturous aeronautic communities in Europe and North America. This prosperous era of innovation and technological growth on aviation extended its developments to all components of the airplane, including the propeller. Donald W. Douglas, head of the Douglas Aircraft Company, considered those communities of people responsible for helping change the world, acknowledging propeller makers and their creations indispensable to succeed [5]. The work on those propulsive devices joined the higher power outputs of the newer engines to the improved body aerodynamics resulting in higher performance aircraft cable of “climb quicker and cruise faster using less power and if need be, fly to safety on one engine” [3].

Since the first effective propellers powered by piston engines, throughout impressive supersonic aircraft and up to modern airliners, a lot changed in the aviation. The aircraft is now a balance between hundreds of different specifications. Some are being improved at the cost of others.

This work studies the evolution of cruise speeds, especially on commercial aviation, in the past century. The trends are presented, and their motives are discussed. In the

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first section, a brief historical overview is presented. The second section discusses the evolution of the flight speed of the airliners since the jet age. The third section exposes the relevance of recover the propeller and its development.

2. Early Jet Age: The Race for Speed

With the invention and development of the jet engine during WWII, gas turbine-powered aircraft expanded the whole flight envelope. Flying higher and faster, both commercial and military jet airplanes ruled the 1950s and 1960s, at what was called: The Jet Age [6].

In comparison with piston airplanes, the speed and ceiling of these first jet-powered aircraft were incredible, and the race for flight speed became the trend [3]. The following years gave birth to a generation of even faster aircraft as the example of the Boeing 727, which had a maximum cruise speed of about 960 km/h [7].

Propeller specialists and companies struggled for their place in the industry, and after a period of uncertainty, they found it with the turboprop. Turboprop appeared as a combination of a gas turbine engine with a more refined and modern propeller. Turboprop aircraft were used mostly on regional commuter transportation, in which less fuel-efficient jet-powered aircraft were not as profitable. See Ref. [8]–[10] for further details on turboprops working principles.

However, the race continued, and in the early 1960s, the Convair 990 could already fly at speeds of more than 1000 km/h [11]. At this time, Douglas, in one of the test flights, accelerated the DC8 to a speed of Mach 1.01 on a 16 seconds dive [12], [13]. But the aviator did not stop there. Mach 1 was reached which means that they need to rush forward. In the early 1970s, jet engine technology was developing at a tremendous pace. It was the age when sharp aircraft noses started breaking through the sound barrier. The Concorde and the Tupolev Tu-144 were developed to cruise at Mach 2 (2200 km/h) [14], [15]. Boeing wanted to create an even faster airplane [16]–[19]. Mach was not serious, and they aimed to fly at Mach 3. It seemed that there were no limits to that race, but something went wrong, and the true supersonic age never came.

The magnificence of supersonic airliners was comparable only to the horror of their ecology and economy. The supersonic engines roar was annoying to the cities' populations, sound booms were destroying everything around [20], and the super-powerful afterburner engines were so hungry for fuel that airlines had to increase the cost of tickets to cover their expenses. The supersonics did not enter mass aviation. To transport ordinary travelers on such planes was the same as to take children to school on supercars. Despite that, new larger subsonic jet-powered airliners conquered the main long-haul routes, and younger models were conquering the regional ones.

3. Commercial Aviation: Higher and Faster! Or not?

It is noticeable that since the 1973 oil crisis, commercial airliners are “losing” their speed from generation to generation. Today, airliners such as the Boeing 737 and Airbus A320 cruise at airspeeds lower than Mach 0.7 (about 830 km/h). The giant flagships like the Boeing 747-8 and the Airbus A380, equipped with four powerful engines, fly at a non-impressing Mach 0.77. And even the most advanced planes of the modern age as the Boeing 787-Dreamliner and Airbus A350 XWB fly at Mach below 0.80. So why are all the airliners, including the most sublime and advanced of our time, lagging the 50-year-old museum exhibits? The reason why airplanes are losing speed is quite complex. The modern aircraft is a tremendous complex system, and aircraft designers must find a balance between hundreds of different specifications. Some are being improved at the cost of others. In Table 1, a comparison of two airliners that operates in the same market segment is presented.

Table 1: Boeing 727-200 vs. Boeing 737 Max 7: Technical Specifications. Data from [7] and [21].

Specifications	**Boeing 727-200**	**Boeing 737 MAX 7**
Manufacturing year	1962	2016
Engines	(3x) P&W JT8D-17R	(2x) CFM LEAP-1B
Fuselage length (m)	46.68	35.56
Wingspan (m)	32.92	35.92
Wing sweep	32^o	25.03^o
MTOW (kg)	95 100	80 286
V cruise (km/h)	1102	839
V max. (Ma)	0.9	0.79
Range – MTOW (Km)	4509	7130
Max Ceiling (m)	13000	12000
Fuel capacity (L)	30620	25816
Capacity (seats)	155	172

The larger size of the aircraft increases the drag. However, that can be attenuated by slightly reducing the speed. Those slightly lower speeds also grant higher comfort to the passengers due to lower noise levels in the cabin. Another noticeable characteristic that differs from the older, faster airliners is the wing sweep angles. As can be noticed in Table 1, the wing of Boeing 727 is smaller but has a bigger sweep than the 737.

Such a wing allows the aircraft to fly faster. Like the newer Boeing 737, many other modern airliners have lower wing sweep than their predecessors. Despite that these modern wing designs have lower sweep, restricting their ability to fly faster, they perform much better on take-off and landings. These modern wings, with better performance at low speeds, make the airplanes easier to pilot. Besides, this lower speed allows flying using less engine's thrust, not only improving fuel efficiency but also significantly reducing noise emissions, which is a very important topic for cities close to airports. The improved performance at low speeds made the take-off and landings much easier and softer improving not only the passengers' comfort but also improving the aircraft's structural efficiency. Older aircraft landed at higher speeds. The touch on the runway and braking were quite punishing, forcing engineers to install reinforced landing gears which took up space inside the aircraft and increased mass. Newer airliners have softer, lighter, and more efficient gears that pleased manufacturers and airlines. Increasing speeds if often expensive in terms of other features. As close is the speed to the sound barrier the greater are the requirements for the aircraft.

One of the main reasons that made the airlines and manufacturers to abandon the race for speed is also one of the main elements of the aircraft: the engine. The heart of most modern aircraft is a jet engine. The task of any jet engine (or reaction engine) is to convert the potential energy of the fuel into the kinetic energy of the jet flow. In practice, the fuel ignites, expands, accelerates and pushes the machine forward. The jet engines used in aviation, use not only their fuel but also the surrounding air, which is also heated up and accelerated to be ejected at high speed by a nozzle to create thrust. See Ref [8] for further insights on jet engines. The Rolls-Royce / Snecma Olympus 593 that equipped the Concorde is a classic example jet engine. But these engines were very greedy. With its small capacity, Concorde had an insane fuel consumption. The much larger, Boeing 747, produced in 1968, turned out to be much more economical [21].

With technological development, the engines received a new, improved design. Turned out that adding another external circuit to a conventional jet engine, the bypass stream, running through this circuit, increases efficiency. The engines become more powerful, and their fuel consumption decreases. These engines were named Turbofans and became a real classic solution in modern aviation. Turbofan engines were much better than turbojets, and with the development of technology and materials, they also began to fly fast. Most modern fighters like the classic F15, Eurofighter Typhoon, Sukhoi Su-30, and the newest F22 and Sukhoi Su-57 fly with these engines. But shortly after the emerge of the turbofans, engineers noticed that the efficiency of the engines increased not only due to the appearance of the external circuit but also due to the increase of its dimensions [23]. More airflow, more effective engine. Since then, the core has been kept generally the same size, and the bypass has been progressively increased.

Improved efficiency not only allows airlines to save money on fuel but also concedes the airplanes to fly further. The comparison between the Boeing 727-200 and the 737 Max 7 (described in Table 1), will be taken into consideration. Both have similar capacities and mass, but the 727-200 has a flight range of about 3500 kilometers, while 737 Max 7 has 7100 kilometers, twice the range of the older one. In terms of the powerplants, the 737 has two engines, while the closest 727 needed three. Figure 2 shows a side-by-side comparison between those two airplanes. The enormous power of the high bypass turbofan engines was the key to the birth of wide-body airliners, which are the main element of global travel today. However, these high bypass turbofan engines have their drawbacks. All aircraft manufacturers faced the same difficulty when upgrading their powerplants. These engines are huge; their diameters are getting bigger, and engineers had to work hard to fit them under the wing of the aircraft. The Pratt & Whitney JT8D installed on 727-200 is much smaller compared to CFM Leap-1B that equips the 737 Max 7 (see Figure 2). The chase for higher bypass ratios dictated this trend. Although, the choice of the Leap-1B to equip the 737 Max 7, that is an upgrade of the Next-Generation 737 family, required changes to the landing gear to maintain the 43 cm ground clearance and also changes to the wing to compensate for the additional engines weight and drag [24].

Figure 2: Boeing 727-200 (right) side-bi-side to a Boeing 737 Max 7 (right)

There are a lot more pros than cons to modern aircraft compared to the older airliners. It is a fact that they fly slower, but the rest of their performance is much better, not only due to modern technology but also because of such compromises.

In Europe, according to [24], short-haul flights (up to 1500 kilometers) within ECAC (ECAC covers the widest grouping of Member States of any European organisation dealing with civil aviation. Currently it is composed of 44 Member States.) bordering countries represented 78.5% of e total IFR traffic in 2017. Also, according to Eurocontrol, in the United States, the share of short-haul flights reached 80.3% in the same period. Even having the technology that allows us to produce faster airplanes, at those distances, a small increase in speed may reduce flight time but has little impact on the journey. The journey is the wait at the airport, check-in, baggage check, passport control, waiting at the terminal, flight, and again the passport control, baggage claim, and the way from the airport to the destination. All these remain stages will not be accelerated, and all the advantages of flight speed can easily be compensated by a traffic jam on the way to the airport.

For airlines, the parameters of fuel consumption and life cycle of the aircraft are more important than the speed of flight. Also, fuel consumption is not only money. Fuel tanks on the aircraft remain the same, and an increase in fuel consumption may result in a reduction of range. It is cheaper for the airline to make the passenger more comfortable, show a couple of movies or provide an extra meal in flight than to speed up the aircraft. From the passenger's point of view, such a deal is also more optimal. The flight may be long, but the level of comfort on those flights is not bad. Higher costs for speed will increase the cost of air tickets and time is a more valuable resource than money just for a small group of people. The world is ruled by economically optimal airliners with economically optimal performance. A cheaper ticket is more important for a passenger and cheaper operation is more important for airlines. Modern airplanes pursue precisely these goals.

4. The Propeller

Propellers are present in different types of powerplants. Propfans, open rotor engines, unducted fans, ultra-high-bypass turbofans, and turboprops have a common factor: all of them rely on the propeller to produce thrust. Between those propeller-driven aircraft powerplant types, turboprops are the most typically found in commercial aviation. Since their first emerge the 1940s, turboprop engines were perceived as a temporary compromise between outdated piston engines and advanced jet engines. Turboprop aircraft flying in the early 1970s were still the same built mainly in the 1950s and, even considered rather obsolete, the industry not seeing great prospects were not particularly in a hurry to create a replacement for them.

Figure 3 shows a comparison of typical propulsive efficiency between different engine types.

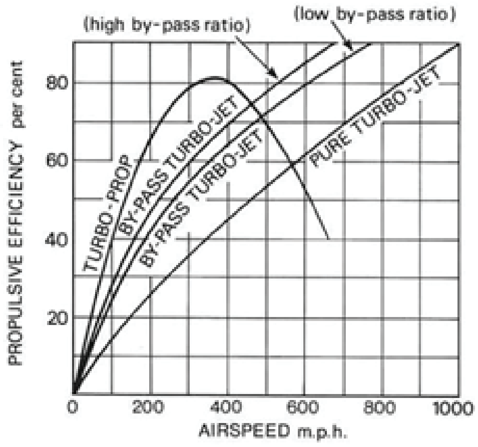

Figure 3: Propulsive efficiency for different engine types. Source [23].

5. The Oil Price Effect in Propeller Progress

In 1973, a severe oil crisis [25] had affected the whole aviation industry. High fuel consumption of the jet engines previously perceived as a perfectly acceptable compromise for speed, now turned out to be a serious problem. Long-range transportation by large aircraft remained profitable, but flights over short distances by regional vehicles were not often paying off [26]. One of the major advantages of turboprop powerplants is its low fuel consumption. In Figure 4, the crude oil prices from 1960 to 2019 is presented. In a period of very high fuel prices, this fact made the airplanes with such engines extremely economically efficient, which also became one of the success factors of companies like Bombardier and ATR, proving that there was a need for aircraft of this class on the market. This economic environment stimulated work towards another reinvention of the propeller for increased fuel efficiency. The Advanced Turboprop Project [28] carried out by NASA was one of the most important work at that time.

In the 1980s and 90s, the airliners market was developing rapidly, and a sharp drop in fuel prices, and as a result, the emergence of a new generation of jets in the early 1990s made all the previous propeller improving efforts, like Advanced Turboprop Project, never materialize. In the early 2000s, a new global economic crisis and a sharp rise in energy prices [31] revived this market. Jet regional aircraft once again became too expensive to operate, and the demand for turboprop engines was rising again.

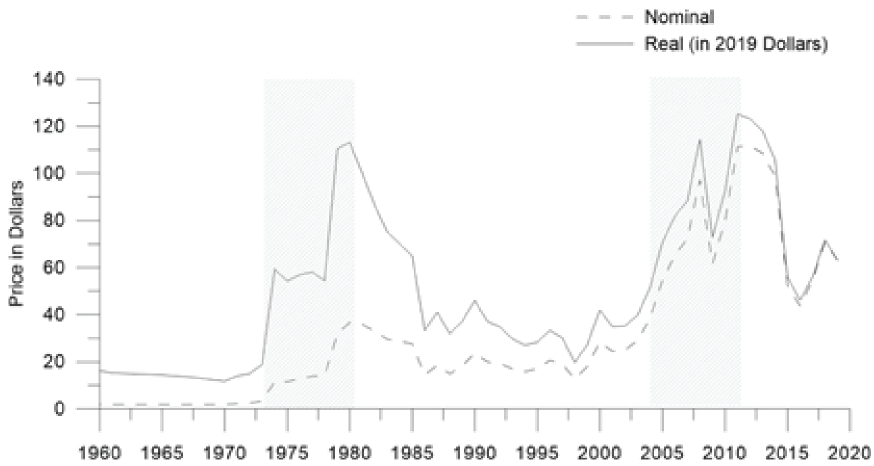

Figure 4: Crude Oil Prices from 1960 to 2019, nominal and real (corrected by the 2019 U.S. inflation). 1960-1985: Arabian Light posted at Ras Tanura; 1986-2019: Brent Spot. Price data source: U.S. Energy Information Administration [29]. U.S. Consumer Price Index (CPI) to correct the prices for the 2019 inflation sourced from the U.S. Bureau of Labor Statistics [30].

5.1. The 1980s' Propeller Avoidance Phenomenon

After the 1980s oil price depression, popular resistance, related to the idea of going back to propeller-driven airplanes, and what it represented in terms of modernity and security, started a propeller avoidance phenomenon on the travelers and thus on the airlines [3]. The turboprop market decreased, and the competition increased. Jet planes were more expensive, consumed more fuel, and were more demanding on infrastructure but had better flight performance in factors such as speed, range, and comfort, making them more attractive to the operators. This fact led to the lowest demand for turboprop airplanes at the beginning of the 2000s [32].

6. Conclusion

The oil price has ruled the progress and technological advance on propellers, the higher the price, the more relevant the propeller-enabled engine development becomes. The industry has played a more reactive than active role in this area, leaving the efforts as soon as the prices drop again.

At the very beginning of the 21st century, the propeller-driven airplane prevailed as a niche. However, this century brought new challenges and priorities. Climate control and pollution are now much serious concerns [33]. Propellers have a role again to play on the progress. Today, the advent of vertical take-off and landing aircraft [34]–[39], also aimed for personal transportation and the widespread unmanned aerial vehicles are bringing the assertion of the propeller as the main choice for low speed, state-of-the-art efficient propulsion devices.

Beyond efficiency, propellers always offered benefits that the jet engine could not. Better take-off and landing performances allow transporting passengers to and from regional, small airports. The military uses turboprop aircraft ever since for transporting soldiers and weapons over all types of terrain and through various forms of restricted airspace. Also, its lower cost allowed enthusiasts and aviators to use them in their recreational, general aviation aircraft. In addition, the demand for turboprop aircraft increased due to a new wave of rising fuel prices, especially in countries that do not have a developed airfield infrastructure. We are living the propeller rebirth.

Acknowledgments

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