The history of modern commercial aircraft focuses on technical developments, sustainable growth and efficiency.

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Abstract. Aviation, an expanding industry, with demand today more than at any point in history, dominates the lives of people, firms, trade, and economies, primarily due to its high transport efficiency. The development of modern aviation trails back from the earliest dreams of flying to the sophisticated, advanced, and environmentally conscious aircraft today. This revolution in technology and sustainability marks significant improvements in various aspects, with the work of many researchers in the past century and beyond. As fundamental subjects proceed to advance, other subjects such as material science, propulsion studies, and aviation chemistry will continue to boost, while new ideas that potentially improve future aircrafts pop up. It seems that it is essential to have a peek back in history, about how the simple structure of fabric and wood comes to be this massive creature in the sky today. After that, this trend in development would head toward a better way, picturing a more preferable future for this industry. This paper explores and provides an overview of the details of this journey, tracing back to the very first aircraft created, to the new technologies of the 21st century.

Keywords: Aviation, sustainable development, efficiency.

1. Introduction

Living in this era where air transport is used so frequently, there is no doubt that the development of modern aircraft is one of the most significant and transformative technological breakthroughs in world history.

Back in the Renaissance, numerous inventors – including the famous Leonardo da Vinci, came up with multiple designs and blueprints of the future aircraft they could barely picture, some of them beyond their time [1]. Thousands of years had passed, and the Wright brothers had struggled to achieve the first fully man-controlled, self-powered flight in 1903, announcing the truly transformative leap of humans into the world of flight. From this time on, due to the vigorous development of fundamental theory work, the past century has been the century with the fastest progress in human aviation. This has led to this relatively stable and well-organised flying system nowadays [2]. Looking back in history, the advancement of which certainly involves three most important aspects: propulsion and power systems, aviation fuels, and materials.

Propulsion systems, firstly, are essential for aircraft to generate thrust, lift, and maintain their positions high up in the sky. This is, undeniably, the fundamental system that supports the operation of aircraft. Going a step further on, to make flights stable, and these journeys more comfortable, or to achieve speeds fast enough to gain consumers or to make air-traveling efficient, better propulsion systems are crucial. All these factors add up to prove the importance of this in the history of aviation. Aviation fuels, on the other hand, are to reinforce the performance of components in the system mentioned above. Many aspects of fuels, like volatility, energy density, and combustion efficiency, very much impact to what extent are aircraft engines efficient or sustainable. A chosen fuel must also be compatible with the materials used to avoid further damage and risks. Therefore, the utilization and decisions of suitable aviation fuels for each aircraft are principles. Lastly, as the conditions required for aircraft to stay at high altitudes are strict, aircraft materials must comply with standards such as being resistant to extreme weather, unexpected situations, and light, or integrating structurally, to improve the performance of commercial aircraft. They also have to be durable and strong to reduce the period of replacing materials and enhance sustainability. The above are all examples of features for suitable aircraft materials which need to be met while developing commercial aircraft.

Nowadays, transportation across borders is essential to enhance these economic and cultural links, indicating the fact that aviation is becoming more and more important [3]. However, worries about continual growth arise, and the aviation industry today is aiming to reduce those impacts while improving efficiency. Hence, this paper aims to look back in history, reflect and explore the key milestones that led to crucial developments of aircraft, examining the possible reasons behind this, while providing a view of future trends, possibilities, and challenges that might be faced in the future of aviation development, especially focusing on sustainability and efficiency.

2. The Development of Modern Commercial Aircraft

2.1. Propulsion and Power Systems

The history of aircraft propulsion systems began when Charlie Taylor built the first ever inline engine for the Wright Brothers. This engine is later classified as a type of "piston engine", along with opposed, V-type, and radial engines – based on how the cylinders are aligned. This type of engine works in a reciprocating manner – taking a mixture of air and aviation fuel through an intake valve, compressing that mixture via a piston, then using a spark ignition, causing combustion, and hence generating power by pushing the gas products out the exhaust valve, and repeating the process, generating thrust by exerting air continuously [4].

These engines then were advanced to rotary engines, aiming for a smoother operation and fewer moving parts compared to traditional piston engines, according to a German engineer, Felix Wankel. They are very similar in terms of drawing in the mixture and combustion, only that rotary engines have this process carried forward by not a piston but a rotor that rotates in a chamber. Compared to reciprocating piston engines, rotary engines have advantages such as a lighter weight or less vibration. However, these engines also have limitations in terms of efficiency due to factors such as more friction while rotating, incomplete combustion, and the need for regular maintenance [5].

There are also general downsides for piston and rotary engines, mostly referring to the amount of sound and heat generated due to their high energy exhaust nature, as well as their similar amounts of hydrocarbon and carbon monoxide emissions, which proves their relatively high-polluting characteristics. Nevertheless, the most significant limitation of piston and rotary engines is that they are not capable of flying at high speeds, due to each of their reasons. For piston engines, fast frequencies of the up and down movement for pistons would create too much friction and cause potential threats of overheating or worn-down components at very high speeds. For rotary engines, on the other hand, there are limits to the maximum rotational speed of rotors due to sealing problems, materials constraints, or combustion chamber effects [6]. These restraints were to be solved later.

Continuing in time, though piston engines had some advancements during the World War 2 periods, making them the primary choice for military aircraft in that era, it must be admitted that there is a more competitive choice emerging – the jet engines – that marks a new leap in the development of power systems. Jet engines, or turbine engines, were the answer to speed problems waiting to be resolved. This term broadly encompasses all engines using jet propulsion, which are to be introduced below. The first jet engines were the turbojet engines, and they are still under production nowadays to achieve high speeds in military aircraft. They work similarly to the piston and rotary engines – all following the fundamental thrust-generating process of internal combustion engines, but with additional components and small variations in the processes.

After the air enters the engine, the compressor, not only a piston, but rows of rotating blades and stationary blades, accelerates the air and heats it, resulting in a higher temperature and pressure before it enters the combustion chambers. After entering these chambers will the air then be mixed with aviation fuel, be ignited, to make chemical reactions happen to release vast amounts of energy – the fluid mixture temperature can be raised to over 1000 degrees. But some of this exhaust gas will not be directly emitted, unlike piston engines, but leads to a turbine connected to the compressor, hence turning its blades and maintaining the operation. The rest of it will be exhausted, driving the aircraft forward. Therefore, the turbojet engines are simultaneous and continuous. Fig. 1 clearly illustrates the components of a turbojet engine.

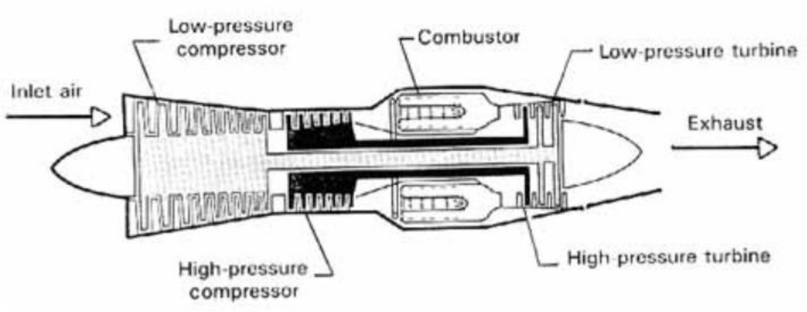

Fig. 1 Primary components of Turbojet Engine [7]

In the compressor specifically, there are multiple shafts with blades that are getting smaller and rotating at increasing speeds going deeper inside it, the function of which is to squeeze the air by this difference, and hence accelerate it.

Advantages of turbojet engines include the well-designed acceleration or compression system, minimum amount of friction as they are free-piston, and the fact that they have high thrust-to-weight ratios, meaning that they take up small amounts of the total weight of the aircraft but still generate a large amount of thrust. This enables them to be used in high-speed, or even super-sonic flights. However, there are still some limitations to be improved, such as low fuel efficiencies or loud noises that influence its sustainability and efficiencies.

In the 1950s, turbofan engines, also the most used engines for passenger and commercial flights, were introduced to public sight. Above turbojet engines, are equipped with a fan located before the air intake channel, allowing a portion of airflow to be sent around but not through the chambers, which creates a reaction force, driving the aircraft forward. The stream of air that proceeds into the intake channel experiences the same process as turbojet engines, mentioned above [8]. Generally, this design can increase fuel efficiency and save fuel to be sustainable concerning turbojet engines, as more thrust is generated by the bypassed air, requiring less fuel through the chambers. It also reduces the amount of noise pollution generated due to the low-speed bypassing air [9]. The flexibility of the design in terms of bypass ratios – the ratio of the air passing by the chambers to which flows in the chambers – enables various applications under different situations.

The extent to which an aircraft is propelled by its power system depends on two factors: the amount of airflow and the speed of airflow [10]. Two specific categories of turbofan engines very much reflect the difference between the two. High bypass ratio turbofans have bypass ratios of greater than 5:1, meaning that for every 1 cubic meter of air passing through the chambers, there are 5 times as much flowing by the chambers. This is an example of the fan moving more air, instead of at a greater speed. There are two main advantages – fewer air flows in the chamber, so less fuel is needed for the same thrust, so this is more efficient, and a thicker layer of air passing by the noise-making core reduces noise pollution, so this type of turbofan engine is more commonly used in modern commercial aircraft [11]. Unfortunately, these turbofan engines usually require large fans compared to the core chambers as the bypass ratio relates to the area ratio, and this creates more limitations, as the fan area cannot be infinitely large, or else the outer circumference of the fan would have a speed beyond which the materials can stand. Low bypass ratio turbofans, however, use more fuel to heat the gases and achieve a much higher velocity – some of which are supersonic – so are used more in military but not commercial flights, so will not be introduced in this paper.

Despite all these different usages and benefits of turbofan engines, there are always disadvantages and drawbacks waiting to be improved. All examples of engines mentioned above are internal combustion engines. In other words, they have similar core logic of performance and methods of generating thrust – simply from reaction forces, burning fuels, and combustions -however, there is another possible substitute – electricity power, and hydrogen fuels.

2.2. Aviation Fuels

One thing that engines, especially the internal combustion engines we use today, cannot work without is aviation fuel. Fuels are involved in these complex chemical reactions to generate power and thrust, finding a suitable fuel improves engine performance and efficiency in various ways. Besides, due to the increasing demand for air-travelling, the amount of carbon dioxide emissions released therefore needs to be controlled [12]. Therefore, the importance of fuel development is self-evident.

Gasoline (AVGAS), something extracted from fractional distillation of fossil fuel, or crude oil, was among the very first aviation fuel applications. It is a mixture of hydrocarbon molecules with carbon atom numbers of 4-8. It is worth noting that AVGAS is distinguished from the traditional gasoline used in car motors. Way before turbojet engines were brought to the public, while piston engines dominated the flight industry in the last century, the primary goal back then was only to find a fuel that could support the relatively low power requirements. At this time, gasoline was considered useful. During war times later on, technological developments led to the introduction of high-octane AVGAS, a more suitable version for piston and Wankel engine-powered aircraft. Something added in this edition is tetra-ethyl lead, a chemical used as an octane booster. The chemical properties of these additives successfully prevent problems that arise in older versions – such as engine knock, formation of ice crystals, and corrosions [13].

However, application defects of AVGAS being used frequently in outdated piston engines are fully exposed today. This fuel, along with the additives, can result in large amounts of lead deposits and halogen contamination, leading to potential cognitive and neurological harm in especially children [14, 15]. Its hydrocarbon content also means more carbon dioxide emissions, threatening a rise in the speed of global warming. Besides sustainability considerations, the high cost involved in refining AVGAS, as well as the reduced supply of fossil fuels indicates a need for an alternative. Yet these worries only exist today. Back in the last century, barely anyone had the awareness of saving non-renewable resources.

Changes occurred following World War II, as jet-powered engines ended the dominance of piston-powered engines and changed the industry, leading to decreases in demand for AVGAS. The development of this implies the necessity of a new type of fuel, and kerosene is what to use. The very first kerosene-based fuel, typically known as Jet A, appeared at this time and was designed specifically to meet the needs of turbojet engines. This fuel has a low viscosity and density and is composed of hydrocarbon molecules with 6-20 carbon numbers, a little more compared to gasoline. This viscosity is carefully controlled to ensure a proper flow, following designed paths, through the fuel system to prevent freezing, despite the relatively low freezing point (-47°C) [16]. Above its properties, after several iterations and updates – in the process of which made Jet A into Jet A-1 – more additives, similar to those in AVGAS, were incorporated to enhance its performance and safety, specifically on anti-icing, corrosion, and anti-deposits.

One significant advantage of kerosene, closely related to turbojet engines, is that it has a relatively high energy density, typically around 35 megajoules per litre [17]. This property enables it to be efficient for supporting not only long flights, but also the required power output for take-off, cruise, and landing, at small volumes and lower costs. This is what made it stand out before other fuel choices for commercial turbojet aircraft. Some other advantages include relatively controlled stability and reliability in storage during flights, particularly due to the low freezing point. This reduces some risks in extreme or cold environments, yet still, there is space for further improvement in aviation kerosene storage [18].

Nowadays, kerosene-contained aviation fuels are widely used to power jet engines. In 2007, statistics show that the aggregate consumption of kerosene globally is roughly 6,800,000 barrels per day [19]. In addition, as time progresses to today, a time when society aims for green and renewable growth, more problems of kerosene become apparent – like those of AVGAS, that kerosene did not solve as a superior substitution. The life cycle of kerosene raises severe environmental impacts such as acidification and the greenhouse effect, as well as less severe ones. These impacts appear not just in engines, but more in the basic refining and transportation processes for this fuel [20]. Besides this, crude oil is expected to face shortages soon, which affects the kerosene industry and hence the aviation industry in terms of costs [21].

Consequently, it is urgent to develop sustainable and alternative fuels for aircraft. One example of this in commercial aviation today is sustainable aviation fuels (SAFs), representing a significant breakthrough in reducing the carbon footprint of aviation. The first SAFs were derived from biomass – dead animals, plants, agricultural residues, and others. This type of SAF is called biofuels. They can reduce carbon dioxide emissions by at least 20% compared to those fuels mentioned above and hence can be used to decarbonize long-haul commercial air travel [22]. From what they are derived from, biofuels can be classified into many categories, such as alcohol-to-jet fuels, oil-to-jet fuels, gas-to-jet fuels, and sugar-to-jet fuels. This is specified in Table 1.

Table 1. Classifications of Biofuels based on Feedstock [23]

Category	Technology pathway	Feedstock
Alcohol to Jet (ATJ)	Alcohol to Jet Synthetic Paraffinic Kerosene (**ATJ-SPK**) or lsobutanol to Jet (ITJ)	Cellulosic biomass, starch, sugar
Gas to Jet (GTJ)	Fisher-Tropsch-Synthetic Paraffinic Kerosene (**FT-SPK**)	Agricultural waste, coal, biomass, municipal waste, natural gas
	Fisher-Tropsch-Synthetic Kerosene with Aromatics (**FT-SKA**)	
Oil to Jet (OTJ)	Catalytic Hydrothermolysis (CH)	Animal fat, recycled oil, vegetable oil and any other bio-oil containing tri-glycerides
	Hydroprocessing Esters and Fatty Acids (**HEFA**) or Hydroprocessed Renewable Jet (HRJ) or Bio-Synthetic Paraffinic Kerosene (Bio-SPK)	Algal oil, animal fat, recycled oil, vegetable oil and any other bio-oil containing tri-glycerides
	Hydrotreated Depolymerized Cellulosic Jet (HDCJ) or Hydrogenated Pyrolysis Oil (HPO)	Agricultural waste, lignocellulose biomass, municipal waste
Sugar to Jet (STJ)	Direct Sugar to Hydrocarbons (DSHC) or Synthetic lso-Paraffin (**SlP**)	Any fermentable sugar
	Hydro-Deoxygenated Synthesized Kerosene (HDO-SK) [Catalytic Upgrading]	Starch, sugar, cellulosic biomass
	Hydro-Deoxygenated Synthesized Aromatic Kerosene (HDO-SAK) [Catalytic Upgrading]	

Most biofuels derived today are ‘drop-in’ biofuels, with similar chemical properties as conventional fuels such as kerosene, meaning that they can naturally mix, according to blending ratios. So, biofuels can be applied to existing engines without the need for too many further adjustments [24].

Other examples of SAFs include synthetic fuels, those obtained from non-biological sources, such as electricity generated from renewable sources, or carbon dioxide captured directly from the atmosphere. Or waste-based fuels, derived from industrial waste materials, such as waste oil [25]. Unfortunately, as SAFs are such a new topic researched, so far, there are not so many mature applications of which, related discussions will be left here.

There are several major obstacles ahead of SAF development and use in commercial aircraft. The key problem among these is that the current costs are too high, primarily due to the advanced technologies and feedstock processing required. Whether the amount of supply for sources can meet the rising global demand for fuels also needs to be considered. Yet still SAFs are good choices for sustainable development, and since most technological research for bio-jet fuels is still in the early stages, more can be expected in the long-term future.

2.3. Materials

The typical lifespan for a commercial aircraft is approximately 35 years, during which it completes tens of thousands of flights [26]. In addition, the severe weather conditions such as low pressure and temperatures aircraft must undergo while transporting speed up wearing out and wearing down their body. Undeniably, in the long term, repair costs are huge, safety issues arise, and sustainability concerns are always present. This is certainly not desirable for the industry and is also the main reason why aircraft maintenance is a topic always worth discussing [27]. Above more efficient repairing, a better choice of aircraft material also plays an important role.

It starts from the early dreams of flying before the first ever aircraft was built. The ancient Egyptians covered wooden frames with balsa wood and muslin fabric, somehow imitating birds' biological composition. Centuries later when the Wright brothers were constructing their plane, the first materials that came to mind were also wood – and fabric, being cheap and convenient to obtain [28]. As air travel in those days was not made into business yet, there was not much demand, for materials, in terms of durability, resistance, and weight, wood seemed to be adequate. However, as time progresses and other sectors – be it engines and fuels – advance, limitations of wood and fabric, such as being resistant to heat, and fragile, start to show.

Aluminium is one of the first metals that took its step into the aviation industry. The first ever engines were made of aluminium, given its heat-resistive nature. Later on, in World War I, as moving towards an era of high-speed aviation, lightweight properties, or high strength-to-weight ratios (SWR) of this metal offered an opportunity for improved fuel and aerodynamic efficiency. The post-war periods and World War II accelerated the spread of the use of aluminium, making it a crucial material frequently used in military aircraft, for instance, Boeing B-17 [29]. Even now, aluminium is still actively in use for its corrosion-resistive feature due to the special oxide layer it forms. Various versions of aluminium alloys, such as the high-strength 7050 and 7091 series, or aluminium-lithium alloys, are developed to enhance their performance in aviation. However, limitations of aluminium still show, including brittleness, abrasion resistance, and worse high-temperature performances in comparison to other metals such as titanium, which requires further advancement [30].

In the 1960s, the aviation industry began experimenting with fibre-reinforced polymers (FRPs). These are examples of composite materials made by embedding fibres into a polymer matrix. This can very much enhance the mechanical properties of polymers. In general, the fibre, or reinforcement, can be made of various materials, such as glass, carbon, aramid, and from natural sources, which share characteristics such as low density, high strength and stiffness. Matrixes usually have good shear properties. Therefore, FPRs are a combination of these, fulfilling all advantages, including high SWR to save weight and improve fuel efficiency, the same corrosion-resistive feature as aluminium, and greater flexibility, enabling moulding into various shapes. In comparison to traditional metals, FRPs are a type of more suitable material for safe, efficient and long-lasting commercial air travel [31]. This information is shown in Fig. 2. Many modern commercial aircraft, such as Airbus A350 and A330, use composite materials to save weight and costs.

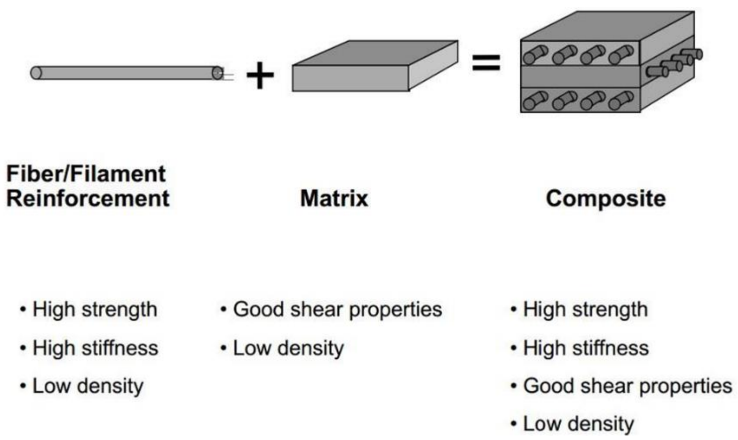

Fig. 2 Roles of Matrix and Fibre in Composite Materials

Carbon fibre-reinforced polymers (CFRPs), specifically, are superior compared to other FRPs, such as glass fibre-reinforced polymers (GFRPs). Carbon atoms can easily form bonds with other atoms, and CFPRs are usually 80-95% carbon-containing. For that reason, CFRPs have low density, but high strength, SWR, and stiffness, enabling better structural performance while maintaining minimal weight [32]. They can also resist temperatures as high as 3000 degrees Celsius, much higher than which required for withstanding chemical reactions and explosions in engines, not like metals, which might experience significant thermal expansion and contraction under ranges of temperatures [33].

In summary, composite materials are widely used nowadays in aircraft construction, and their market is expected to quadruple at a compound growth rate of 7.3% by 2026 [34]. Estimations also forecast that the use of composite materials in the global aviation industry can meet 20-25% of the carbon dioxide reduction targets, making air travel more sustainable [35]. However, CFRPs can have significant disadvantages. There is a larger amount of energy or electricity required to manufacture it, which is – mostly – derived from fossil fuels. Therefore, although the use of CFRPs itself reduces emissions in aviation, this reduction is replaced by the increases in manufacturing industries [36]. In recent years, governments and businesses have invested in improving the properties of composite materials exploring new fibre types, exploring the potential of FRPs, and fixing present problems in the manufacturing processes of these materials, aiming to reduce costs and enhance efficiency [37]. So, future possible improvements in sustainability should be expected.

As time moves onto the 21st century, there is more interest raised in the applications of nanomaterials and other smart materials in aviation. Nanomaterials are characterized by structural dimensions from 1 to 100 nanometres, which provide their distinct properties compared to other materials. Two main categories of nanomaterials include nanocomposites, which embed nanoparticles into matrixes, and carbon nanotubes (CNTs), which are cylindrical nanostructures. These structures usually provide enhanced mechanical properties, such as more tensile strength and elasticity, as well as better thermal and electrical conductivity [38]. They can significantly improve the performance of aircraft along with FRPs (that account for 50% of aircraft's structural weight) by being used along, and possibly improve the safety of air travel by reducing threats from lightning strikes [39, 40].

Examples of other smart materials include shape memory materials (SMMs), including shape memory alloys and polymers (SMAs and SMPs), which are defined as materials able to return to their original shape after deformation, exposure to high temperature, and electric or magnetic fields. By cooperating with FRPs or nanomaterials, aircraft functioning and efficiency can be further improved [41].

3. Conclusions

Technically speaking, the advancements from this aspect had been driven by innovations in mainly aircraft propulsion systems, fuel, and materials. The transition from early piston-engine aircraft to the era of jet propulsion revolutionized air travel and enhanced its efficiency, by improving travelling speed and range, which enabled aviation to serve not only the military. The introduction of various fuels reduced operation costs significantly, and this interacts with newly developed materials to improve fuel efficiency. Notable milestones include the transformation from aviation gasoline to kerosene, as well as the use of metals and composite materials. Through the last century, thanks to all those ways to improve flying efficiency, the meaning of aviation has changed – flying is no longer only a dream of discovery, but something commercialized and made into a business, contributing to the economy and globalization today.

Parallel to technology, awareness of sustainable growth has been raised, when time moves into the 21st century. Realizing how much the aviation sector contributes to global warming, later developments have increasingly prioritized sustainability. This has led to significant efforts to reduce emissions – not only during journeys but in manufacturing processes of related components as well.

Developments such as biofuels, FRPs, and nanomaterials represent big steps toward reducing carbon footprint in air travel, making our world healthier, and our possible future more long-lasting.

Looking into the future of commercial aviation, as governments are investing in research focusing on sustainability and efficiency, it is worth expecting more advancements in this term. Continued improvements in material science, propulsion technology, digital systems, and many other sectors will work together to shape the next generation of modern aircraft. Breakthroughs in history are usually through new ideas and experiments, therefore it is reasonable to say that if innovation carries on, driven by the pursuit of cheaper, more environmentally friendly, and efficient aviation, there will be a better future.

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