CARBON NANOMATERIALS IN AEROSPACE APPLICATIONS

NAVJEET KAUR [a], ATUL PRATAP SINGH [a*]
Department of Chemistry, UIS, Chandigarh University, Mohali, Punjab

[*]Email: *atulpiitd@gmail.com*

Abstract
Carbon nanotubes (CNTs), introduced over two decades ago, have garnered widespread scientific interest, particularly for their prospective applications in aerospace. The unique mechanical, thermal, and electrical properties of CNTs suggest significant implications for the future of aircraft and spacecraft. This paper explores the anticipated implementations of CNTs in various aerospace applications, encompassing commercial planes, military aircraft, rotorcraft, unmanned aerial vehicles, satellites, and space launch vehicles. The focus extends to potential uses in hydrogen storage encapsulation, lightning protection, icing mitigation, airframe/satellite weight reduction, and addressing challenges associated with future space launches. The research delves into both existing and novel CNT applications in aerospace, examining concerns related to health and safety. The findings contribute to a comprehensive understanding of the evolving role of carbon nanotubes in shaping the future of aeronautics and astronautics.

Keywords: *Carbon nanotubes; aircraft; aerospace; nanomaterials*

1. Introduction

In the late 1950s, Roger Bacon at Union Carbide made a groundbreaking discovery while studying carbon under conditions near its triple point. During this exploration, he observed elongated hollow carbon tubes encased in graphitic carbon layers, evenly spaced apart similar to the layers of planar graphite. Morinobu Endo later observed these gas-phase-produced tubes in the 1950s, some of which were covered by a single sheet of wrapped graphite. The potential uses of Carbon Nanotubes (CNTs) have multiplied across various fields, including energy storage, mechanical engineering, sensing, biological applications, and field emission [1]. Given the specialization of aerospace engineering, it is foreseeable that CNTs will play a significant role in shaping its future. These nanotubes have the potential to be a game-changer in the materials used in aerospace engineering, particularly in light of the retirement of the space shuttle and the increased adoption of composite materials in current and future commercial aircraft, such as the Boeing 787 and Airbus A380 [2]. To achieve controlled synthesis of carbon fibers, a catalytic chemical vapor deposition (CVD) system was employed in one method.

The advancement in polymer-based carbon fiber research initiated with microscale filaments, leading to the experimental detection of carbon nanotubes through transmission electron microscopy [3]. An analysis of the current literature on carbon nanotubes indicates a substantial increase in scientific papers on this subject since the year 2000 [4]. This growing trend is expected to persist as scientists delve deeper into the applications and properties of carbon nanotubes in various industries. Notably, the usage of the phrase "aerospace" in publications related to carbon nanotubes has seen a significant rise, from 0.25 percent in 2012 to 1.8 percent in 2013 [5]. While current implementations are somewhat limited, these numbers suggest a promising future for CNT applications in aeronautical sciences. The literature search for CNT applications in aeronautical engineering often reveals in-depth research findings in material sciences. Although a few articles specifically focus on the potential uses of CNTs in aeronautics and astronautics, the multidisciplinary nature of the subject makes a comprehensive review challenging. This paper aims to provide a general overview of the concepts related to the use of carbon nanotubes in aeronautical sciences from a material science standpoint. It acknowledges the vast amount of research activities in nanotechnology, particularly with carbon nanotubes [7], and seeks to cover the essential issues and potential applications of CNTs in aeronautical sciences. The focus is on comprehending these concepts, and when more thorough information is available, it is presented with reference. The descriptions are provided from the perspective of material science.

2. A quick overview of carbon nanotubes

Because of the multiple advantageous applications of carbon nanotubes in various scientific domains, a wide range of published research on these materials has looked at many of their properties.

2.1. The classification system

There are two primary types of carbon nanotubes: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). SWCNTs consist of a cylindrical tube formed from a single sheet of graphite. When viewed normal to the tube's axis, a group of concentric tubes is revealed in MWCNTs. The conductivity of SWCNTs is determined by the roll direction with the tube structure and the sheet of graphite, represented by the two integers (n, m) [8]. The chiral vector (Ch) in this context is analogous to a twist vector. Carbon nanofibers (CNFs) have a length-to-diameter ratio exceeding 100, similar to MWCNTs in structure. However, they are generally longer, and their distinction from CNTs lies in the alignment of the graphene plane. A structure is classified as a CNT if the graphene plane and the fiber axis are parallel; otherwise, it is considered a CNF [9]. Popov extensively covers the production, growth mechanism, optical characteristics, electrical transport, vibrational properties, mechanical qualities, and thermal properties of carbon nanotubes.

2.2 Synthesis of CNTs

Prior to the discovery of multi-walled carbon nanotubes (MWCNTs) and single-walled carbon nanotubes (SWCNTs), the arc-discharge process was employed in the manufacturing of carbon fibers and fullerenes [9]. MWCNTs were first identified in soot resulting from this procedure by Iijima [10]. In the arc discharge synthesis of SWCNTs, metal catalysts were initially utilized temporarily. Another noteworthy method is laser ablation, as employed by Thess et al. Chemical vapor deposition (CVD) catalyzing the formation of nanotubes, pioneered by Yacaman and others, is also a significant approach (Fig. 1) [11]..

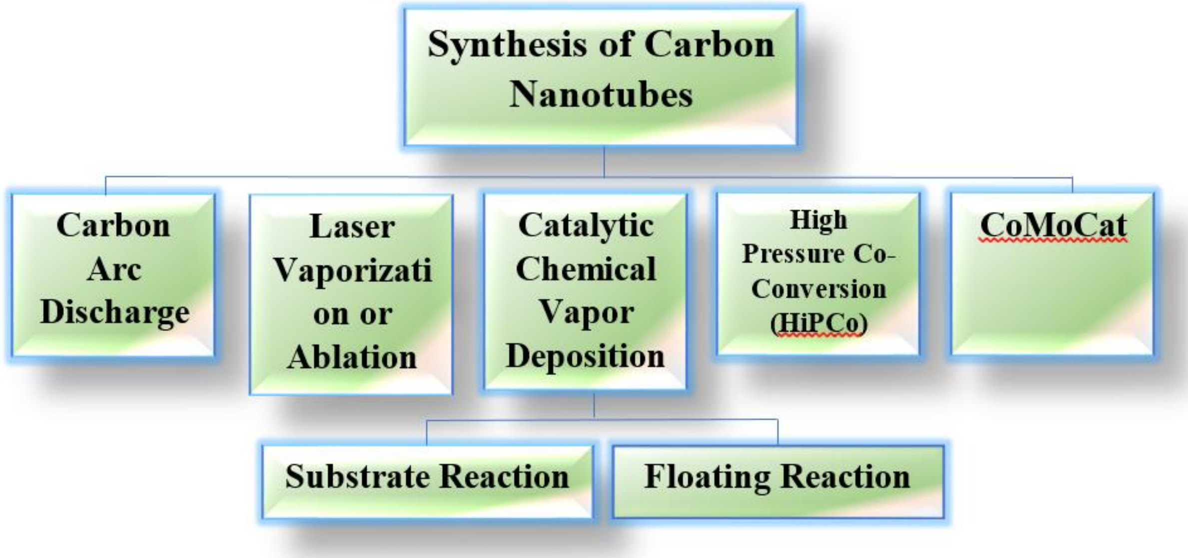

Fig. 1| Synthesis of CNTs

2.3 Production

In current applications, Carbon Nanotubes (CNTs) find utilization in various products, existing in a dispersed state within thin sheets or as powders [12]. However, to achieve commercial viability, seamless integration into established manufacturing processes is imperative. Notably, the optimal values for CNTs are yet to be ascertained, a challenge that ongoing research aims to address. There is a continuous improvement in their production methodologies, owing to extensive investigations into these materials. A recent study by Wang et al. highlighted the development of CNT composites showcasing exceptional multi-functionality, boasting record-high strength (3.8 GPa), a high Young's modulus ($E = 293$ GPa), and notable electrical conductivity ($K = 41\ W\ m^{-1}\ K^{-1}$) [13].

2.4 Properties

Single-Walled Carbon Nanotubes (SWCNTs) generally exhibit sizes within the range of 0.8–2 nm, whereas the diameters of Multi-Walled Carbon Nanotubes (MWCNTs) fall between 5 and 20 nm.

Notably, instances of MWCNTs with diameters surpassing 100 nm have been documented [12]. The outer diameter of MWCNTs typically spans from 2 nm to 20–30 nm, while the inner diameter varies according to the number of layers, ranging from 0.4 nm to a few nanometers. The axial size of MWCNTs extends from 1 m to a few centimeters, featuring ends capped with half-fullerene molecules, presenting a dome-like form marked by pentagonal defects. The primary purpose of these half-fullerene molecules (pentagonal ring defects) is to effectively seal the ends of the nanotube [14].

2.5 Modeling of Carbon Nanotubes

Modeling of Carbon Nanotubes (CNTs) stands as a crucial component in advancing our understanding of their potential applications and inherent characteristics across various disciplines. Diverse computational techniques, including growth simulations [15][16], structural mechanics analyses [17], finite element analysis (FEA) [18][19], and electron field growth simulations [20], have been employed to unravel the intricacies of CNT behavior. Rafii-Tabar has notably contributed by providing a comprehensive overview of computational modeling, specifically focusing on the thermo-mechanical and transport properties of CNTs [21].

3. Aerospace CNT applications chronology

The chronological progression of significant events related to the adoption of Carbon Nanotubes (CNTs) in aircraft sciences is depicted along the time axis. Notably, while the time axis designates 1991 as the year of CNT discovery, it is imperative to acknowledge that substantial research and observation on fullerene materials had taken place before this milestone [22][23]. The exploration of nanoscale tubular carbon filaments, a precursor to CNTs, dates back to 1952 [24], although it took some time for the associated publications to be translated into English. Despite the pre-existing evidence of CNTs, the attribution of the discovery year to 1991 has garnered attention within material sciences and chemistry [25]. This is the declared commencement of the CNT era in aerospace sciences, as it marks the birth year of Multi-Walled Carbon Nanotubes (MWCNTs), a consequence of the scientific impact of Iijima's seminal article published in 1991 [26]. The novelty and wide dissemination of this work throughout the scientific community, spanning various engineering disciplines, solidified its significance. In 2010, NASA unveiled an extensive roadmap outlining the future applications of nanomaterials, particularly emphasizing the role of CNTs [27]. The roadmap highlighted potential benefits in aerospace applications, including reduced vehicle mass, heightened functionality and durability, improved damage tolerance, enhanced self-healing capabilities, superior thermal protection, and control. Moreover, CNTs demonstrated promise in advancing energy generation and distribution.

However, the integration of CNTs in aerospace applications faces several challenges. These include the development of large-scale production techniques for CNTs, ensuring uniform dispersion in composite materials, addressing alignment and adhesion issues with CNTs in reinforced polymers, comprehensively understanding their toxicity, and achieving consistent volume and size in CNT production. Overcoming these challenges is pivotal for unlocking the full potential of CNTs in aerospace sciences and realizing the envisioned advancements in materials and energy applications.

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4. CNTs' Roles in Aviation

4.1 Basic Introduction

Newer models of aircraft, rotary-wing aircraft, unmanned aircraft vehicles, and missiles will have to meet more demanding standards in terms of weight, visual and thermal signature, acceleration, and maneuverability. These needs, on the other hand, necessitate the development of sophisticated materials and systems capable of incorporating these features. Carbon nanotubes are good candidates to address these needs because they can be used in a variety of technologies. Schilthuizen and Simonis'[28] research highlights several essential technologies for using nanotechnology in aeronautics. Nanotechnology applications in ICT, remote and unmanned guiding, and power, in particular, are highlighted as potential operating areas in aeronautics. While this research covers the entire field of nanotechnology, this part will focus primarily on CNTs and some of their potential applications. This section focuses on reducing weight by replacing current airframe materials and circuitry, resulting in lower fuel usage. The advantages of CNT adoption for aviation icing, aircraft lightning protection, propulsion systems, and safety concerns are also discussed.

4.2 Commercial planes and carbon nanotubes

The advantages of employing carbon nanotubes in aerospace applications originate from their outstanding qualities, which include a superior strength-to-weight ratio, as well as mechanical, electrical, and thermal properties [29]. Given that nanomechanics is an important field for the development of aeronautics and the aerospace industry [30]. The weight of a vehicle will play an important role in future commercial and military aircraft and space vehicles, as it has a direct impact on operating costs. The aerospace sector is continuously faced with the task of introducing a light airplane or spacecraft without sacrificing structural integrity. According to Gohardani et al 's [31] latest study, the two most important factors that will most likely affect future commercial aircraft that use dispersed propulsion technology are total weight and propulsive power. Furthermore, in connection with Gohardani's first suggested official definition for distributed propulsion technology in subsonic fixed-wing aircraft, materials with CNT implementation is deemed crucial for future designs in the aerospace sector [1], [32].

4.2.1 Airframe

Due to their high aspect ratio and combination of a large surface area for a given volume, they have reinforcing effects, nanocomposites have been the topic of several research endeavors in various scientific domains, including aeronautics [33]. In this context, nanoparticle dispersion and a lot of stickiness at the particle matrix are critical, with immediate negative consequences for mechanical characteristics [34]. In some review studies, the various characteristics of polymer matrix nanocomposites have been thoroughly examined [5], [35]. O'Donnell [36] and colleagues' [37] simulation tests on commercial aircraft are among the few studies that have looked into the influence of CNTs on commercial aircraft in the "heavy" aircraft category, according to the FAA's requirements.

4.2.2 Wiring

An intriguing prospect in aeronautics lies in the potential for weight reduction and lower fuel consumption through the replacement of conventional copper wiring with lighter Carbon Nanotube (CNT) wires [38][39]. Currently, the copper wiring on commercial airliners, such as the Boeing 747, extends over approximately 135 miles and weighs around 4000 pounds [40]. TE Connectivity experts assert that the utilization of a CNT-based cable, specifically the 1553B, can result in a remarkable 69 percent reduction in weight [41]. Beyond the significant weight advantage, the substitution of copper wires with CNT alternatives offers additional benefits. Vibration fatigue, oxidation, corrosion, and premature failures caused by overheating, common concerns with traditional copper wiring, can be mitigated through the implementation of carbon nanotube (CNT) cables. Looking ahead, CNT data cables are anticipated to emerge as pivotal technologies for both passenger and freight vehicles by 2025, forming an integral component of the baseline vehicle and preferred system concept (PSC) vehicles. This transformative shift aligns with the broader objectives of the ERA (Environmentally Responsible Aviation) initiative. Under the guidance of NASA, Northrop Grumman, as part of its N2 advanced vehicle research, conducted investigations to determine an optimal aircraft layout that achieves the specified environmental goals while maintaining current safety standards. The integration of CNT-based cables showcases a tangible advancement in material technology, contributing not only to weight reduction but also to enhanced durability and safety standards in the aviation industry..

4.2.3 Icing of aircraft

The domain of aircraft icing stands out as a promising area within aeronautics where the utilization of Carbon Nanotubes (CNTs) could yield significant benefits. This phenomenon arises when airborne water droplets, supercooled or below freezing, collide with an aircraft's surfaces during flight [42]. The type of icing encountered depends on factors such as the density of liquid water per cubic meter, influencing the severity of the condition. Aviation icing on fixed-wing aircraft introduces detrimental effects, including reduced lift and stall angle of attack, along with an increase in profile drag [43]. Take-off scenarios, with ice accumulation on wing and tail surfaces, can further lead to control and stability issues.

Additionally, ice build-up on propulsion system components can hamper efficiency and increase drag. In the quest for mitigating these challenges, researchers have long sought icephobic external surface materials for anti-icing applications in aviation [44]. Notably, Gohardani conducted a comprehensive analysis of various aerospace materials, considering their intrinsic qualities to evaluate the potential use of CNTs in anti-icing applications [45]. Key properties under scrutiny included ice adhesion, static and dynamic wettability [118,119], and rain erosion properties [46].

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4.2.4 Thermal defense

To increase the limits of thermal stability and mechanical integrity under various aerothermal flow conditions, carbon nanotubes are now being integrated into a variety of thermal protection materials. Research is also being done to make special task-specific material systems, such as thermal protection systems (TPSs) used to shield spacecraft from radiation and the heat of re-entering the atmosphere, multipurpose. The phenolic-impregnated carbon ablator (PICA), a special TPS system, was enhanced with CNTs to increase its char strength and shield it against micrometeoroid impacts. It was anticipated that CNTs will strengthen the char by giving a second fibrous structure to the pyrolysis region's otherwise randomly oriented pyrolysis. When compared to standard PICA material, bulk performance as measured by established TPS test techniques revealed a significant improvement in mechanical resilience.

4.2.5 Propulsion

In propulsion applications, carbon nanotubes have been discovered as propellant additions for chemical propulsion systems of the future. The advantages of using nanoparticles, according to Law [49], [50], include the possibility to minimize agglomeration, quicker ignition, increased overall heat release rate, and increased burning rate for functionalized/catalytic particles. The US department of Energy has lately conducted research on the application of nanocomposites in gas turbines, particularly erosion-resistant coated compressor air foils [51]. Reduced carbon emissions brought on by improved compressor efficiency, more engine power, and prolonged engine life were some of the study’s possible advantages. In recent years, both scholars and the public have become interested in the usage of alternative fuels for aeronautical applications. The development of synthetic jet fuels, LNG, and hydrogen as substitutes for currently utilised jet fuel is particularly intriguing [52].

4.2.6 Usage of resources on-site

The challenges inherent in human space exploration, particularly the need for astronauts to repair rather than replace equipment in remote locations with limited resources, underscore the importance of In-Situ Resource Utilization (ISRU). Microwave radiation has been identified as a promising tool for efficient heat conversion [50]. Addressing the imperative for repair capabilities, NASA Johnson Space Center and Rice University collaborated on a breakthrough by successfully integrating multiwalled carbon nanotubes in low weight percentages into pre-ceramic materials. These materials are crucial for repairing reinforced carbon-carbon thermal protection systems, particularly significant in the aftermath of the Shuttle Columbia disaster. The core of this innovative repair material system revolves around a specially formulated pre-ceramic polysilylene-methylene copolymer, transforming into a silicon carbide ceramic at high temperatures (~850 and 1200 °C). This method of material processing holds potential for utilization in ISRU, particularly in the context of materials retrieved from planetary surfaces. The application of such advanced materials extends beyond space exploration to commercial sectors, notably in the aircraft industry. The commercial aircraft business places great emphasis on ensuring the quality and repairability of materials. For nano-enhanced materials to gain approval, especially from regulatory bodies like the US Federal Aviation Administration, adequate pathways for repair and maintenance must be established. However, there is a notable gap in public and private funding for the qualification, testing, and certification of materials for use in commercial aerospace applications. While initial funding and attention have been provided by government research agencies, widespread industry adoption in the commercial sphere is yet to be conclusively demonstrated. Addressing these challenges is crucial for unlocking the full potential of nano-enhanced materials in both space exploration and commercial aviation.

4.2.7 Life support

Long-duration human space travel poses significant challenges, making Environmental Control and Life Support Systems (ECLSS) technologies an area rich for innovation with nanoengineered materials. Reliable air, water, and food supplies, effective waste management systems, and habitable living space are critical for both short-duration missions in the relative safety of low Earth orbit (LEO) and projected long-duration missions, including those to Mars. While there are currently no operational ECLSS systems utilizing nanomaterials in space, the comparatively lower reliability and performance of existing systems justify the exploration of nanomaterials to enhance overall system performance. For the crucial ECLSS function of removing CO2, Carbon Nanotubes (CNTs) have been functionalized with secondary amines, offering potential advantages over existing systems, including improved regenerability and reduced power consumption. Water recovery and purification, another essential ECLSS function, present challenges even in ideal circumstances, and these challenges are amplified in a microgravity environment with the requirement for long-term resilience. Nanomaterial-based water filtration systems, including those utilizing carbon fullerenes, have shown promise. NASA-sponsored nanoscale filtration technology employing CNTs has even been successfully developed into a commercial product. The exploration of perforated graphene as a material for water filtration is gaining traction, drawing substantial investment from the aerospace and defense sectors, although scalability concerns persist [52]. As advancements in nanomaterial-based technologies continue, the potential for improving ECLSS systems becomes increasingly evident. The integration of these materials has the potential to revolutionize life support systems for extended space missions, ensuring the sustainability and success of human exploration beyond Earth's orbit.

4.2.8 Protection from lightning

The expanding use of composite materials in aircraft applications has some cost-effective benefits, including better fuel efficiency and lower noise and pollutant emissions [53]. Likewise, due to the change in material qualities, such changes create additional issues. The potential of lightning strikes on airplanes is one of the areas vulnerable to such a risk. According to a statistical in-flight study, a commercial airliner is subjected to a lightning strike every 1000–10,000 flying hours, or around one lightning strike per year [54].

4.2.9 Electromagnetic interference shielding

Radio frequency radiation sources and reliable electronics are subjects to electromagnetic interference shielding (EMI). As a result, electronics should also be shielded adequately, as under-shielding can result in product failure and overshielding contributes to material cost and weight increases. In addition to the electronics of aircraft, polymer matrix composites are well established in several diverse applications. Since their inception, these materials have been used for their light weight, simple processing, and easy manufacturing. As of today, PMCs can be filled with a variety of materials. Because of their high conductivity, CNTs have become increasingly popular since their introduction. Reflection, absorption, and internal reflections are the methods that are used for shielding EMI.

4.3 CNTs and military planes

New scientific criteria about stealth qualities, material characteristics, performance in risky circumstances, and the dearth of pilots, onboard future military aircraft are enforced as the development of future military aircraft progresses, including sixth-generation planes and beyond. The envisioned concept for the united states air force (USAF) for the years 2025 and 2050, according to Froning and Czysz , aneutronic fusion propulsion, magneto-hydrodynamic (MHD) airbreathing propulsion, augmentation of MHD and fusion power with power from the quantum vacuum's zero point energies and augmentation of vehicle jet propulsion with field propulsion to double the vehicle's delta V [55].

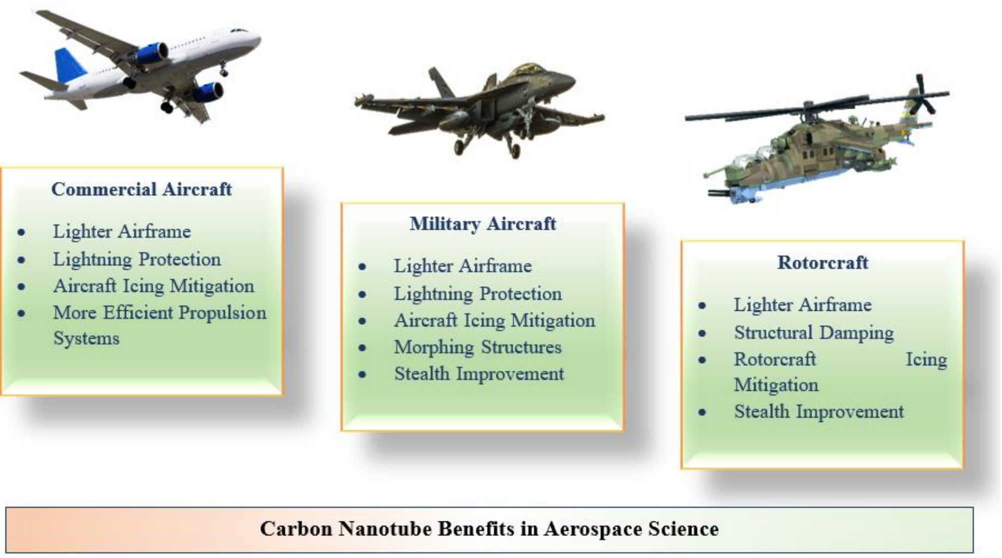

Fig. 2| Carbon Nanotube Benefits on Different Aerospace Sector

5. Opportunities and Challenges

The landscape of nanomaterials innovation is a global concern, spurred by diverse commercial applications in areas such as medical and energy. This marks a departure from historical trends where aerospace and defense initiatives, such as carbon-fiber-reinforced plastics, were primary catalysts for materials innovations. Today, leaders in the aerospace nanotechnology community recognize the need for a new level of collaboration across various stakeholders, including commercial, scientific, systems, and production engineering, to drive the development and utilization of nanomaterials. Unlike the past, government funding from defense research and technology programs is no longer the primary driver of advanced materials, at least in the context of Europe and the US. Anticipating that internal research and development efforts of both defense and commercial contractors will prioritize the creation and integration of nanomaterials for aeronautical applications may be somewhat unrealistic. Developing well-understood materials produced at scale and at a market-acceptable price poses significant challenges, often entailing high costs and risks. Innovative approaches, such as "materials-genome" level modeling and simulation, coupled with experimental testing and characterization methodologies, as advocated by Meador, represent potential strategies for lowering development costs. This modeling effort aims to more accurately bridge carbon nanotube length scales, ensuring that performance predicted by models aligns closely with experimental outcomes, translating into practical macro-scale applications. While government-sponsored aerospace science and technology programs are expected to continue receiving significant funding, there is a growing awareness that collaboration and cross-disciplinary efforts are essential for the aerospace industry to remain competitive and to stay ahead, or at least keep pace, with advancements in nanoengineered materials seen in other commercial sectors. The adoption of these materials holds the key to transformative changes in aerospace technologies..

6. Conclusions

A look back at the subjects discussed in this study reveals a complex picture of CNTs in aeronautical applications. As soon as the technical difficulties have been thoroughly addressed, the adoption of these materials in aircraft engineering will deliver revolutionary breakthroughs, as seen here. Similarly, the potential use of carbon nanotubes in aeronautical sciences raises a slew of multi-layered terrestrial and safety concerns and celestial health, as well as long-term performance evaluations. The advantages of CNT use in aeronautical engineering for use on the ground and in space applications have been shown. Although there are now just a few applications of carbon nanotubes in aeronautical sciences, the reasoning in the medium and long term, potential uses for these materials in aircraft engineering will come to pass. Despite the current scientific obstacles, it is common knowledge that the implementation strategy will be aided by new nanotechnology concepts.

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