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Statistical Analysis of Airfoil Usage in Aircraft

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Abstract

The study aims to answer how frequently airfoils are used in fixed and rotary wing aerial vehicles produced both individually and based on airfoil families. Frequency distribution analysis of airfoil utilization in fixed-wing and rotary-wing aircraft helps in understanding design preferences and performance needs and constraints. The literature study provides the history of airfoils, the subjects mostly studied regarding airfoils and mentions the current state of the field. The study investigates the airfoil families to which the wing profiles of approximately 6,000 fixed-wing and approximately 450 rotary-wing aircraft belong through frequency distribution. The results indicate that in fixed-wing aircraft, NACA airfoils are used in 52.2%, Clark-Y airfoils in 8.2%, Goettingen airfoils in 5.9%, Wortman airfoils in 4.8%, and TsAGI airfoils in 3.1%. When considered as singular airfoil use rather than airfoil families, Clark-Y is the most widely used airfoil, followed by the NACA 23XXX series. In rotary-wing aircraft, NACA 0012 and NACA 0015 airfoils, both symmetrical profiles developed by NACA, are the most widely used. The study is valuable as it provides statistical data on the use of both airfoil families and singular airfoil design in fixed and rotary-wing aircraft. However, it is important to note that the airfoil data is incomplete, and the study aims to provide a general impression of the findings.

1. Introduction

Airfoils are wing profiles used in fixed-wing aircraft, helicopter rotor blades, wind turbines, fans, propeller blades, and more. The most well-known types of airfoils include symmetrical airfoils, axisymmetric airfoils with positive camber, reflexed airfoils, flat bottom airfoils, supercritical airfoils, and supersonic airfoils (biconvex, double wedge). Common airfoil families include the National Advisory Committee for Aeronautics (NACA) airfoils, Goettingen (GOE) airfoils, Wortmann FX airfoils designed by Hermann Wortmann, TsAGI airfoils from the Russian Central Aerodynamics and Hydrodynamics Institute, Eppler airfoils designed by Richard Eppler, Selig airfoils designed by Michael Selig, the Royal Aircraft Factory (RAF) airfoils designed in the United Kingdom, and the United States Air Force (USAF) airfoils. These are commonly used airfoil families (Anderson, 2011). Most used airfoils often represent optimal choices for performance in terms of lift, drag, aerodynamic efficiency and stability. Fixed-wing aircraft require airfoils that provide efficient lift-to-drag ratios, good stall characteristics, and stability across various flight regimes. Helicopter rotor blades require airfoils that provide good lift-to-drag ratios, minimize retreating blade stall, and maintain performance at varying angles of attack while reducing vibration and noise (Russel,1996).

Airfoils used in the period before the first flight were non-optimized; they were very thin and highly cambered. In 1884, H.F. Phillips patented some airfoil shapes. Subsequently, Octave Chanute, Otto Lilienthal, and the Wright brothers conducted pioneering studies on thin and highly cambered airfoils (Greydanus, 2020). In 1910, Joukowsky created a complex plane airfoil from a circle using conformal mapping. One of the challenges associated with the Joukowsky airfoil is its cusped trailing edge. To address this issue, the Kármán–Trefftz transform was developed, allowing for a non-zero angle at the trailing edge (Burington, 1940; Milne, 1973). In the late 1920s, NACA developed four-digit airfoils representing a series of extensively tested geometric features such as maximum thickness, maximum camber, and the location of maximum camber on the chord (Allen, 2017).

Laminar flow airfoils are specifically engineered to maintain extended periods of advantageous pressure gradients. Typically, laminar airfoils exhibit favorable pressure gradients that typically extend from around 30% to 75% of the chord length (Dwyer, 2013). The Clark Y airfoil, designed in 1922 by Virginius E. Clark, is often used in light aircraft and model airplanes. It is a well-known and widely used airfoil with a flat bottom and a curved upper surface (Anderson, 2011). During World War II, German aerodynamic experts initially proposed the concept of the supercritical airfoil. Supercritical airfoils have a flat upper surface, blunted trailing edge, reduced camber, and rearward-moved maximum thickness. These airfoils are designed to enhance aircraft performance in the transonic speed ranges, where the primary goals are managing shock waves and reducing drag (Harris, 1990). The journey of the airfoil design process is illustrated in Fig. 1 (Greydanus, 2020).

Figure 1. Historical Evolution of Airfoil Designs (Greydanus, 2020)

In natural laminar flow (NLF), the air flows smoothly and parallel to the object's surface, with minimal disruption and turbulence. Key characteristics of NLF include smooth flow, low drag, and delayed boundary layer separation. NLF airfoils notably enhance an aircraft's overall aerodynamic efficiency and fuel economy (Somers, 1981). Slotted airfoils are incorporated to enhance an aircraft's lift properties, focusing primarily on improving performance during takeoff and landing, as well as contributing to the prevention of stalling. In modern Boeing aircraft, triple-slotted flaps, when not actively engaged, align flush with the wing. When fully deployed, they maintain attached airflow to the flap's surface, preventing flow separation (Parlett, 1971; Gudmundsson, 2013).

A laminar separation bubble is an aerodynamic occurrence on an airfoil's surface, marked by the transition of the boundary layer flow from a smooth, laminar state to a turbulent state. This transition leads to the separation of the airflow from the airfoil's surface before reattaching downstream. Therefore, controlling and managing laminar separation bubbles is a critical aspect of minimizing drag and maximizing lift (Gaster, 1967). Low Reynolds number airfoils are specially designed airfoil shapes optimized for Micro Aerial Vehicles (MAVs), mini–Unmanned Aerial Vehicles (UAVs), gliders, and smaller wind turbines. Low Reynolds number airfoils have higher camber and a thicker profile compared to other airfoils (Selig et al., 1989).

The inverse design of airfoils aims to create airfoil shapes with specific performance characteristics or desired properties, starting with a known airfoil shape. Inverse design begins with a set of desired performance criteria and works backward to create an airfoil shape that meets those criteria (Volpe, 1983). Methods such as the PARSEC (PARametric SECtion) method, Bezier curves, NACA airfoil parameters, or other mathematical functions are used for parametric representation (Sun et al., 2018). The design parameters for camber and thickness distribution are then established. It is common to utilize artificial neural networks, genetic algorithms, gradient-based techniques, or other optimization algorithms. This process is typically iterative, with ongoing adjustments made until the desired performance criteria are achieved (Quagliarella & Vicini, 2001; Secanell et al., 2006; Jahangirian & Ebrahimi, 2017).

Recent research in airfoil design focuses on optimizing boundary-layer parameters to enhance aerodynamic performance. Collazo and Ansell (2023) proposed a framework that generates pressure distributions to achieve desired boundary-layer characteristics, resulting in significant drag reductions for optimized airfoils. Their method, validated through experimental campaigns, proved effective in improving aerodynamic performance. Krishna et al. (2021) emphasized the importance of airfoil design in determining lift and thrust requirements, utilizing computational fluid dynamics (CFD) for analysis. Asan et al. (2023) numerically investigated NACA 0018 airfoil with slot at various angles of attack. Glaws et al. (2022) studied invertible neural networks enable rapid inverse design of airfoil shapes for wind turbines. Xu and Wu (2023) worked on numerical optimization of airfoil design, including the effects of angle of attack, thickness, and additional tips, as well as using machine learning to predict lift and drag. Patel et al. (2023) examined the design of two new airfoils optimized for low Reynolds number rotary wing applications.

After providing a comprehensive historical overview of airfoil development and discussing the current challenges faced in the field, the main objective of this study is to bring out the utilization of airfoil frequency distribution. Specifically, we aim to analyze the prevalence and distribution patterns of airfoils used in both fixed-wing and rotary-wing aircraft. This investigation will be carried out by employing frequency distribution techniques, allowing us to gain insights into the frequency at which different types of airfoils are utilized across various aircraft types.

2. Materials and Methods

In 2010, Dave Lednicer made a significant contribution to the field with his comprehensive work titled "The Incomplete Guide to Airfoil Usage." Lednicer's exhaustive study serves as a valuable resource, offering detailed airfoil data for a wide spectrum of aircraft and rotorcraft. This seminal work, available to the public through the University of Illinois Urbana-Champaign (UIUC) airfoil data website, consolidates information on airfoil usage across various aviation applications. Within Lednicer's compilation lie detailed records encompassing airfoil data for approximately 6,000 fixed-wing aircraft types and nearly 450 rotary-wing aircraft. This vast repository provides researchers and aviation enthusiasts alike with invaluable insights into the aerodynamic profiles utilized in aviation engineering.

For the purposes of the current study, our analysis focuses specifically on the airfoils employed in the inboard sections of aircraft wings. This strategic decision acknowledges the potential variability in airfoil selection across different segments of an aircraft's wing structure. By concentrating our investigation on the inboard sections, we aim to ensure a more precise examination of airfoil utilization trends and patterns.

Throughout the data analysis phase, we employed a rigorous approach, utilizing frequency distribution as a fundamental statistical tool. Airfoil profiles exhibiting frequencies falling below a predefined threshold were systematically categorized as "others." This strategic categorization served to streamline the presentation of our study's findings, ensuring clarity and coherence in the results. A frequency distribution, a cornerstone of statistical analysis, provides a graphical or tabular representation illustrating the frequency of occurrence for various values or categories within a dataset. By systematically tallying the occurrences of each specific value or category, frequency distributions offer a structured and condensed overview of the dataset.

For a 4 digit NACA airfoil (NACA 00XX), the equation for the airfoil's thickness distribution is given in Eq. 1.

$$y_t = \frac{t_{max}}{0.2}\left[0.2969\sqrt{\frac{x}{c}} - 0.1260\frac{x}{c} - 0.3516\left(\frac{x}{c}\right)^2 + 0.2843\left(\frac{x}{c}\right)^3 - 0.1015\left(\frac{x}{c}\right)^4\right] \quad (1)$$

where y_t=half-thickness at any point along the chord, t_{max}=maximum thickness as a fraction of the chord length, x=distance along the chord, and c=chord length of the airfoil.

The camber line equation varies depending on whether you are in the region before or after the location of maximum camber equation for the airfoil's camber line height is given in Eq. 2 and Eq. 3.

For x≤p·c

$$y_c = \frac{m}{(p)^2}(2p\frac{x}{c} - (\frac{x}{c})^2) \quad (2)$$

For x>p·c

$$y_c = \frac{m}{(1-p)^2}((1-2p) + 2p\frac{x}{c} - (\frac{x}{c})^2) \quad (3)$$

where y_c=camber line height at a given, m = maximum camber (as a fraction of the chord), and p = position of maximum camber along the chord.

Beyond mere tabulation, frequency distributions serve as powerful analytical instruments, enabling researchers to extract valuable insights regarding data distribution. They facilitate the identification of underlying patterns, trends, and measures of central tendency within the dataset, thereby enhancing our understanding of the phenomena under investigation.

3. Result and Discussion

In the results section of our study, we meticulously present the outcomes derived from our analysis. This presentation encompasses findings pertaining to both airfoil families and individual airfoil designs, offering a comprehensive overview of the distribution patterns observed within the dataset. In Fig. 2, wing profiles commonly utilized in aircraft are categorized by airfoil families. NACA has the highest value, with 3112, far surpassing all others. This suggests NACA's dominance in the domain being measured, possibly airfoil design or use. Clark Y and Goettingen also have significant contributions with 487 and 349, respectively. Wortmann and TsAGI show moderate contributions with values of 284 and 187. USAF, NASA, and RAF have notable entries, suggesting their active roles in this field, with the USAF having 117 and NASA at 97. Smaller contributions are observed from researchers or organizations like Eppler, Curtiss, and Aeromarine. Other holds the second highest value (787), which likely represents a collection of entities or airfoils not specifically listed.

The NACA airfoil family demonstrates significant prevalence, with 52.2 out of every 100 airfoils belonging to this category. Nearly half of all fixed-wing aircraft employ airfoils from the NACA family. Following NACA, the next most frequently used airfoil is the Clark-Y, along with its modified versions, comprising 8.2 out of every 100 airfoils. A notable portion of aircraft wings also utilize airfoils from the German Schools, with 5.9 out of every 100 airfoils belonging to the Goettingen family, and 4.8 to the Wortmann family. Subsequent airfoil families include TsAGI, RAF, USAF, NASA, Boeing, and Eppler. Of these, 3.1 out of every 100 airfoils belong to the TsAGI family, 2.8 to RAF, 2.0 to USAF, 1.6 to NASA, 1.5 to Boeing, and 1.0 to Eppler. Additionally, 13.2% of the airfoils were categorized as 'other' due to their association with less common airfoil families. Notable individual airfoil designers include Curtis Robin, Mark Drela, Gustave Eiffel, Robert Liebeck, John Roncz, and Michael Selig. Moreover, various institutions have contributed to airfoil design, including the Aeromarine Plane and Motor Company, the German Research and Development Establishment for Air and Space Travel (DFVLR), IAW airfoils of the Polish Air Force, and Delft University airfoils.

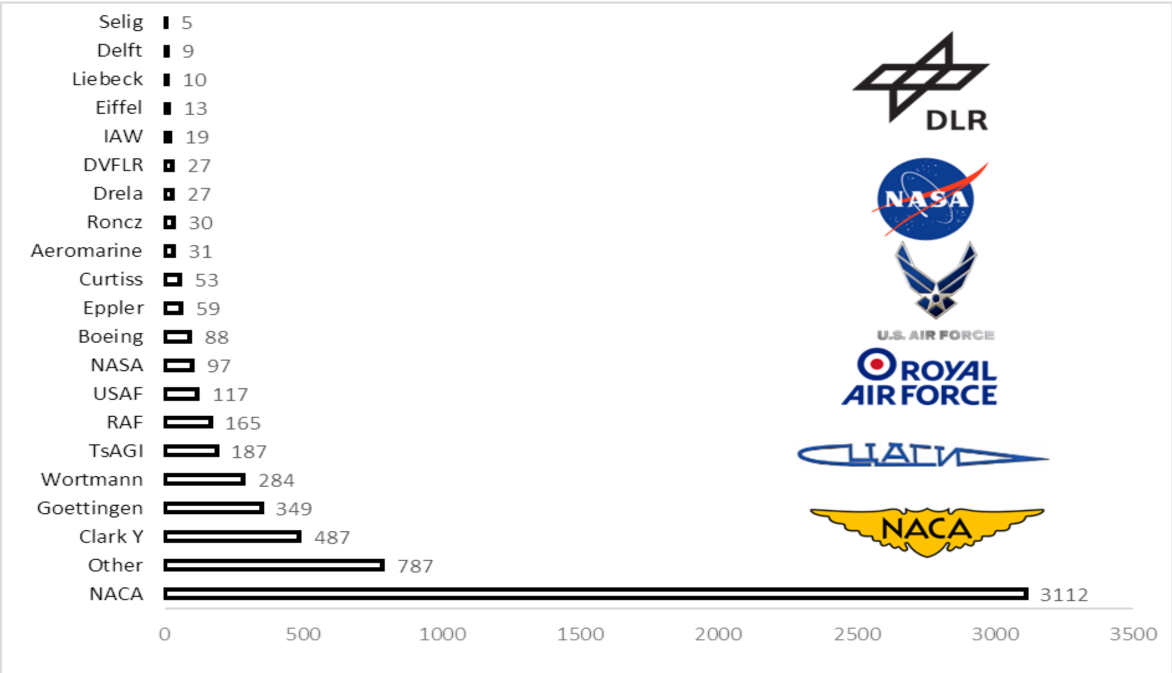

Figure 2. Frequency distribution of airfoil family usage in approximately 6,000 fixed-wing aircraft.

When assessed on an individual design basis rather than by airfoil family, the Clark-Y airfoils, along with their modified versions, emerge as the most prevalent. Their widespread use underscores their effectiveness in diverse aircraft applications. Following closely behind are the NACA 5-digit series airfoils, exemplified by profiles such as NACA 23012, 23015, and 23018, renowned for their versatility and performance across various flight regimes. Additionally, the NACA 4-digit series airfoils, including variants like NACA 2215, 4412, and 2412, hold considerable significance in aircraft design due to their favorable aerodynamic characteristics. In Fig. 3, the frequency distribution of individual airfoil usage in fixed-wing aircraft has been meticulously sorted from the most to the least prevalent. Clark Y airfoil has the highest number of occurrences or usage with a value of 487. It is a widely recognized airfoil that has been extensively used historically, especially in aviation. NACA 23012 follows with a value of 205, showing significant usage but not as much as the Clark Y airfoil. Other NACA airfoils (like NACA 23015, NACA 23018, NACA 2215, NACA 4412, NACA 2412) have progressively smaller values, ranging from 149 down to 105, indicating less frequent usage but still notable representation in the dataset. This graphical representation offers a clear visualization of the prevalence of each airfoil type within the dataset, providing valuable insights into industry trends and design preferences. Furthermore, it is noteworthy that both the Clark-Y and NACA 4412 airfoils exhibit geometric similarities, as illustrated in Fig. 3. This resemblance underscores the importance of recognizing common design features and their impact on aircraft performance and aerodynamic behavior.

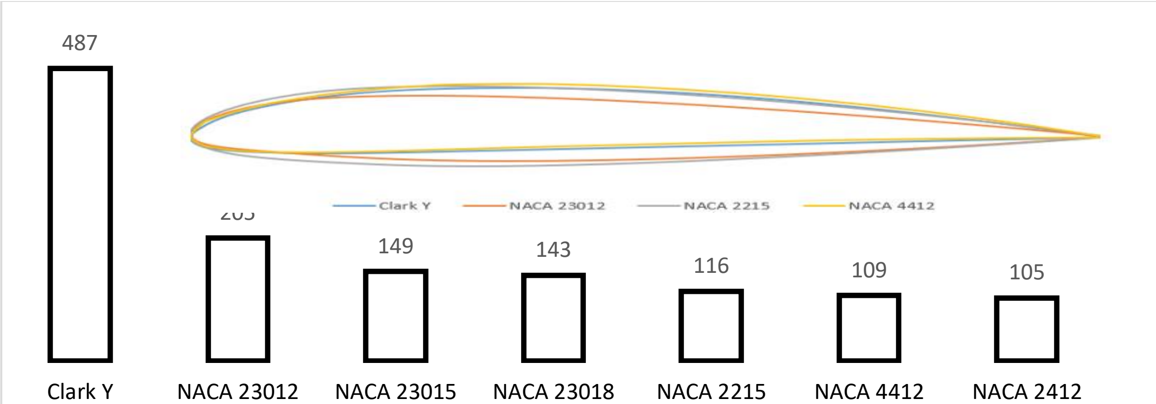

Figure 3. Frequency distribution of airfoil usage in approximately 6,000 fixed-wing aircraft.

Frequency distribution of use of NACA airfoils in 3,112 fixed wing aircraft is shown in Fig.4. NACA 23012, NACA 23015, and NACA 2412 stand out among the individual airfoils, with values of 205, 149, and 105 respectively. These profiles are prominently used, as depicted by their larger representations in the chart. A range of other NACA airfoils is listed, with values between 20 and 83. These include more specialized airfoils like NACA 4415 (74), NACA 2213 (42), and NACA 64A215 (37). The NACA airfoil family boasts widespread adoption of both its 5-digit and 4-digit series across fixed-wing aircraft. Among these, the NACA 5-digit series, represented by profiles such as NACA 23XXX and 63XXX, stands out for its versatility and performance across a range of flight conditions. Similarly, the NACA 4-digit series, characterized by airfoils like NACA XX12 and XX15, enjoys extensive usage owing to its favorable aerodynamic properties and well-established performance characteristics. In addition to these commonly utilized series, certain airfoil designs within the NACA family have gained prominence in fixed-wing aircraft applications. Notably, the 6-digit series features airfoils such as the 64A215 and 64A212, which have found widespread acceptance due to their favorable lift and drag characteristics. Furthermore, the NACA M-6 and NACA M-12 airfoils, both conceived by the renowned aerodynamicist Max Michael Munk, occupy a significant position among the repertoire of commonly used wing profiles in fixed-wing aircraft. These airfoils, crafted with precision to meet specific aerodynamic requirements, have garnered recognition for their exceptional performance and suitability across a range of aircraft designs and missions.

Frequency distribution of Wortmann FX, Goettingen (GOE), and TsAGI airfoil usage in fixed wing aircraft is shown in Fig.5. The counts range from 4 to 97, with most Wortmann FX models having relatively low frequencies (under 20) and a few having higher frequencies. The mode among the specific Wortmann FX models is 4, occurring three times for models 81-K-130/17, 67-K-170 mod, and 66-H-159. Aside from "OTHER", the most common Wortmann FX models are: 61-184 and 67-K-170 and 61-163.

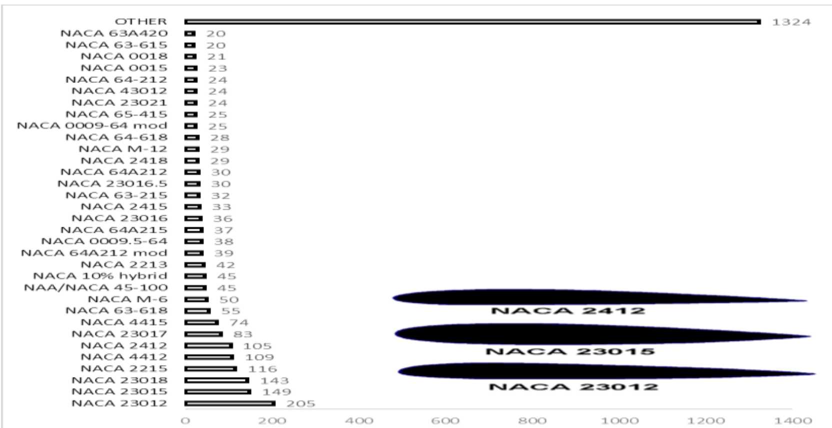

Figure 4. Frequency distribution of use of NACA airfoils in 3,112 fixed wing aircraft.

The Wortmann FX airfoil family encompasses several widely utilized wing profiles, with standout examples including the FX 61-184, FX 61-163, and FX 67-K-170. Renowned for their aerodynamic efficiency and versatility, these airfoils have become staples in the design of various fixed-wing aircraft, offering superior performance across a range of flight conditions. Similarly, within the Goettingen airfoil family, several wing profiles have emerged as favorites among aircraft designers. Notable examples include the GOE 549, GOE 387, GOE 535, and GOE 398 airfoils, recognized for their favorable lift-to-drag ratios and stable aerodynamic characteristics. These profiles are widely employed in the construction of both experimental and production aircraft, contributing to enhanced performance and stability. In contrast to other wing profile families, the TsAGI series boasts a diverse array of wing profiles tailored to suit different aircraft types and mission requirements. Among the most prevalent TsAGI wing profiles are the TsAGI R-II and TsAGI SR-5S, each accounting for a significant portion of usage within their respective aircraft categories. Both fixed-wing and rotary-wing aircraft prioritize airfoils that enhance lift and minimize drag. The primary difference lies in the operational requirements-fixed-wing airfoils are optimized for sustained high-speed flight, while rotary-wing airfoils are designed for variable speeds and dynamic conditions. It's worth noting that rotary-wing aerial vehicles commonly employ symmetrical airfoils due to their unique aerodynamic requirements and operational characteristics. Frequency distribution of airfoil usage in a sample of 450 rotary-wing aircraft is given in Fig. 6. The counts range from 5 to 153, with most models having relatively low frequencies (under 20) and a few having very high frequencies. The distribution is highly right-skewed (positively skewed), with many low-frequency models and only a few high-frequency ones. Among these, the NACA 0012 and NACA 0015 symmetrical airfoils stand out as the most prevalent choices in rotary-wing aircraft design. The NACA 0012 airfoil, characterized by a symmetrical shape with a thickness of 12%, holds a dominant position in rotary-wing applications, constituting 27.1 out of every 100 airfoils analyzed. Similarly, the NACA 0015 airfoil, with a symmetrical profile and a thickness of 15%, emerges as another commonly used option, representing 9.5 out of every 100 airfoils.

Additionally, our analysis revealed the utilization of other notable airfoils in rotary-wing aircraft design. For instance, the NACA 23012 airfoil, a modified version of the NACA 0012 with enhanced aerodynamic performance, accounts for 4.4 out of every 100 airfoils. Moreover, the Boeing VR-7, NACA-8-H-12, and ONERA OA211 airfoils also make notable appearances, representing 4.2, 2.2, and 1.8 out of every 100 airfoils, respectively. These findings underscore the prevalence of specific airfoil profiles in rotary-wing aircraft design, highlighting the importance of selecting airfoils tailored to meet the unique aerodynamic demands of helicopter rotor blades and other rotary-wing applications.

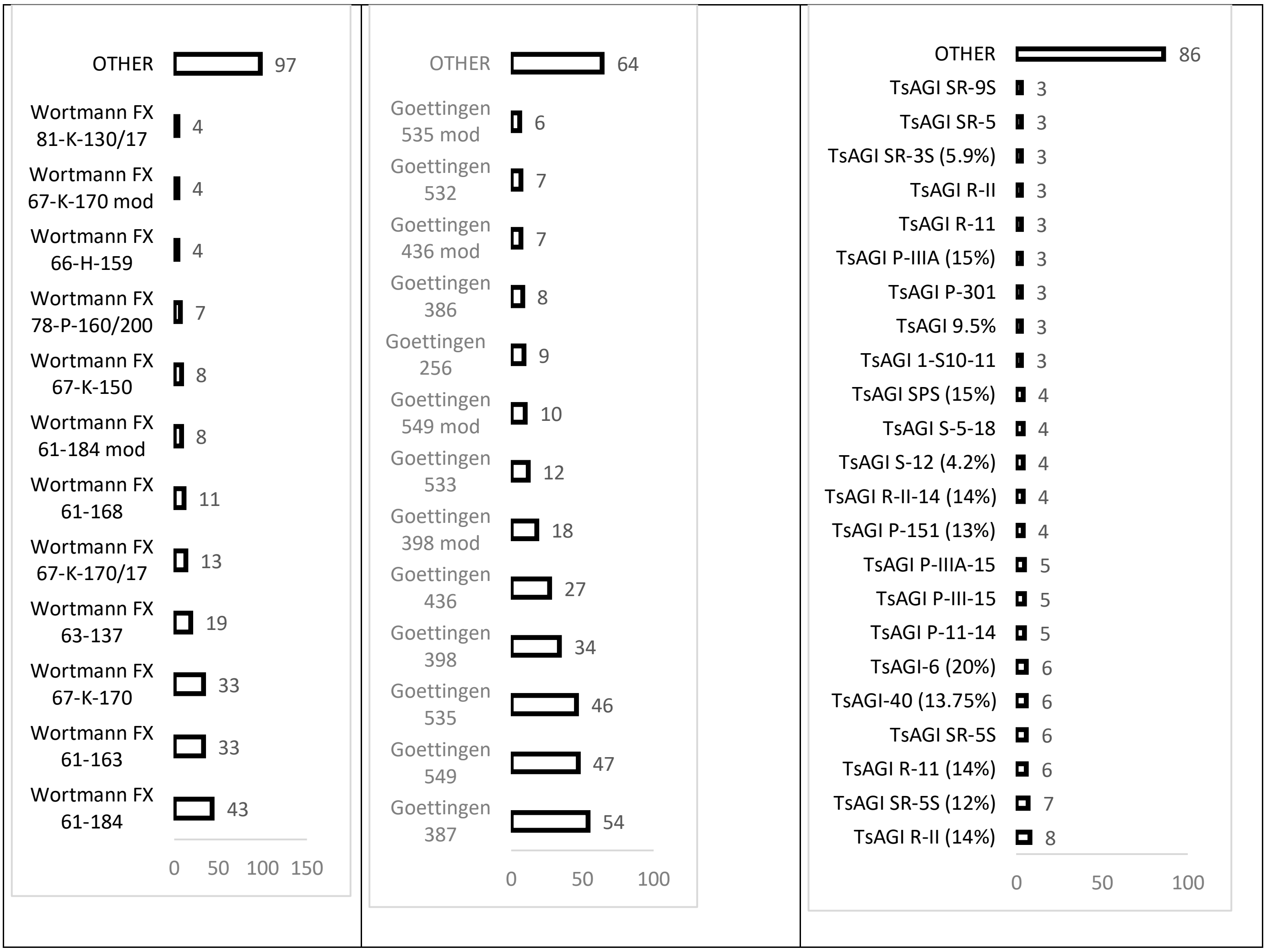

Figure 5. Frequency distribution of Wortmann FX, Goettingen (GOE), and TsAGI airfoil usage in fixed-wing aircraft: analysis of 284, 349, and 187 profiles, respectively

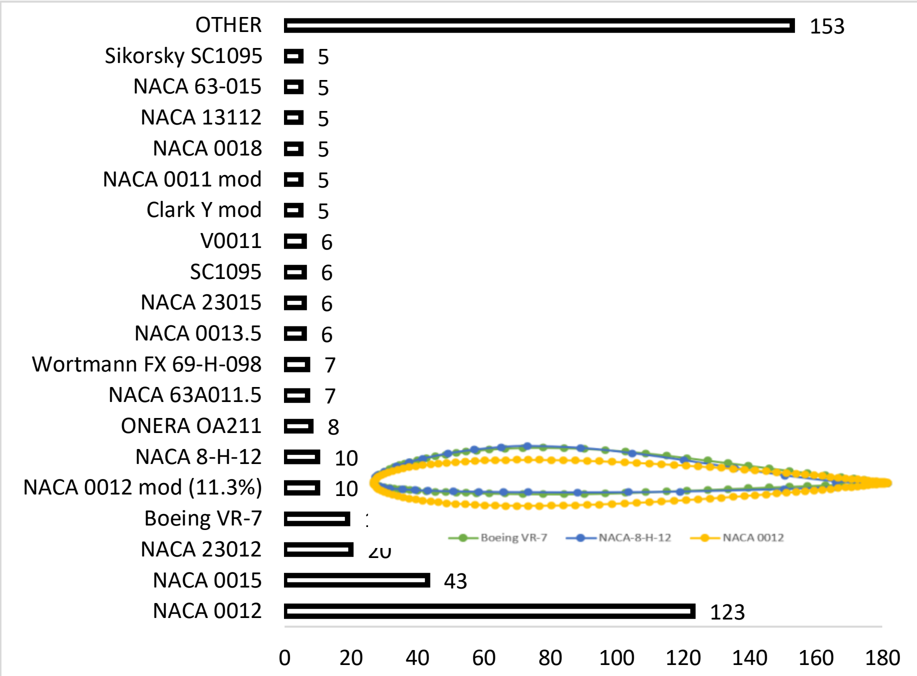

Figure 6. Frequency distribution of airfoil usage in a sample of 450 rotary-wing aircraft

The preference for different wing profiles could be the subject of another study. In this study, the reasons why the Clark Y airfoil, one of the most used wing profiles, is widely employed are discussed. The Clark Y airfoil is widely used in aircraft design due to its versatile and favorable characteristics across various flight conditions. The Clark Y features a flat bottom surface, which simplifies construction and makes it easier to manufacture. This flat undersurface also provides stability when the airfoil is placed on a flat surface, making it useful for wind tunnel testing and theoretical analysis. Relatively high lift-to-drag ratio, good lift characteristics at low angles of attack, making it suitable for a wide range of aircraft. The airfoil's design also allows for a gentle stall characteristic, which is crucial for safety in low-speed flight conditions. Additionally, the Clark Y exhibits predictable behavior across different Reynolds numbers, making it adaptable to various aircraft sizes and speeds.

4. Conclusion

This study focuses on examining the utilization of airfoil designs in both fixed-wing and rotary-wing aircraft. To achieve this, the study conducts a frequency distribution analysis of various airfoil families associated with approximately 6,000 fixed-wing and roughly 450 rotary-wing aircraft. The introductory section provides a historical overview of airfoils and categorizes the current research conducted in this field. The findings reveal that in fixed-wing aircraft, NACA airfoils are employed in 52.2% of cases, followed by Clark-Y airfoils at 8.2%, Goettingen airfoils at 5.9%, Wortman airfoils at 4.8%, and TsAGI airfoils at 3.1%. When considering singular airfoil design types rather than families, Clark-Y emerges as the most frequently used airfoil, closely followed by the NACA 23XXX series. In rotary-wing aircraft, symmetrical profiles like NACA 0012 and NACA 0015 are the predominant airfoil choices. It's important to note that while this study provides insights into the prevalence of airfoil usage in aircraft, the presence of incomplete data means that its aim is to offer a general impression on this subject rather than definitive conclusions. Future studies can improve upon these findings by updating frequency distributions and expanding the scope of the study with more comprehensive data.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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