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# A review of the fighter airfoils from first-generation to fifth-generation

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**Abstract.** In the field of air control, fighter has always played a vital role. Airfoil, as an indispensable part of fighter, has always been attached importance to research and development. Since the 1940s, the airfoil shape has undergone many significant changes, and the technical level has gradually realized from subsonic to transonic and then to supersonic. This paper mainly analyzes and summarizes the design characteristics and changing trends of the airfoils by analyzing the aerodynamic shapes of the first to fifth generation fighter airfoils. The performance that the airfoil needs to meet gradually improves over time. In the new era, the demand for airfoil design is more diversified. Countries pay attention to improving the aerodynamic performance, stealth performance, mechanical stress structure, material technology and morphing technology of airfoils. To meet the development needs of the new generation of fighter, this paper proposes that it is necessary to improve the level of stealth technology and morphing technology of fighters, and at the same time, improving of the CFD and the Navier-Stokes equations matter a lot. What's more, the comprehensive application of multidisciplinary technology may make the future fighter more information and intelligent.

**Keywords:** fighter airfoil, aerodynamic performance, trans-generation, transonic airfoil, stealth performance.

## 1. Introduction

On July 19, the South Korean KF-21 fighter prototype completed its first flight, and the Ministry of defense of the Republic of Korea positioned it as a 4.5-generation semi fighter. At present, nine countries in the world can develop supersonic aircraft. In order to cope with the increasingly complex air battlefield environment in the future, the research and development of a new generation of fighter has become the development focus of major military powers, and is an important competitive field to seize the new military commanding height [1]. Therefore, it is very meaningful to roughly sort out the development and changes of the airfoils of the first-generation fighter aircraft to the fifth-generation fighter aircraft airfoils currently in service.

This paper collects information from recent papers about airfoils and aerodynamics, then analyzes and summarizes the aerodynamic advantages and development trends of the first to fifth generation of fighter airfoils. Comparing with the airfoils of the previous generation of fighter, people are able to further understand the advantages of the trans-generation fighter and the necessity of airfoil design innovation through this paper. The next-generation fighter airfoil will not only make breakthroughs in aerodynamic efficiency, but also have better morphing technology and stealth performance.

## 2. Airfoil development typical examples and analysis

After World War II, fighter airfoil designs emerged in an endless stream. Each airfoil corresponds to the specific flight performance that the aircraft needs to meet. Each generation of airfoils represents a leap in the aerodynamic performance of fighters. Airfoils can be classified by curvature, symmetrical or asymmetrical airfoil. Also, there are other methods such as shape, theoretical airfoils or empirical airfoils and so on. CLARK–YH airfoil, NACA 0012 airfoil, NACA 64A204 airfoil and F-35A are chosen as the typical examples.

### *2.1. First-generation: CLARK–YH airfoil*

The yak-18 is a two-seat primary trainer designed and produced by the Yakovlev Design Bureau of the Soviet Union after the Second World War. This airfoil is a very classic generation design. Its airfoil is thicker at the front, with the thickest point being about 30% of the airfoil. The shape presented by the cross-section has a large curved upper camber, but an almost flat lower camber (Figure 1). Its designed applicable speed range is subsonic speed range, it can have a large lift force under the condition of small air resistance, and it is easy to manufacture. Characteristics are shown in Table 1.

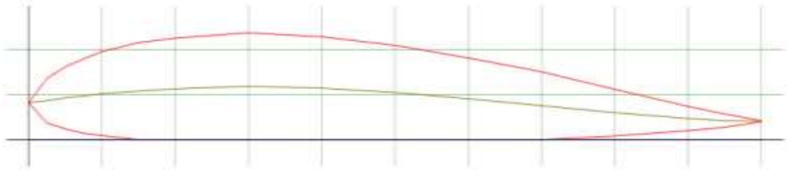

**Figure 1.** CLARK–YH airfoil [2].

**Table 1.** Clark–YH airfoil characteristics [2].

| Characteristics | Values | Characteristics | Values |
|---|---|---|---|
| Max. thickness | 11,9% la 30% x/c | Max. AoA | $9^0$ |
| AoA at $C_{d0}$ | -2.0 | AoA at $(C_l/C_d)_{max}$ | $4.5^0$ |
| Max. arrow | 5.95% at 30% x/c | $C_{l\ max}$ | 1.11 |
| $(C_l/C_d)_{max}$ | 32.834 | $C_l$ at $(C_l/C_d)_{max}$ | 0.683 |

PRISACARIU, Vasile did the aerodynamic analysis through software Javafoil, Profoil and XFLR5 to calculate the basic parameters in Table 2.

**Table 2.** Basic parameters of Clark–YH [2].

| Conditions | Value | Conditions | Value |
|---|---|---|---|
| Angle of attack (AoA) | $-5^0 \div 13^0$ | Speed | 10÷30 m/s |
| Nr. Reynolds | $2x10^5$ / $4x10^5$ / $6x10^5$ | Density | 1,22 kg/$m^3$ |
| Iterations | 100 | Viscosity | 1,5x$10^{-5}$ $m^2$ /s |

With the help of the data of three Reynolds numbers in the Table 1.2 and the software, conclusion can be inferred that the lift coefficient decreases with decreasing Reynolds number and increases with increasing maximum angle of attack for a fixed value of drag coefficient [2].

Using software to perform aerodynamic analysis of Clark–YH can provide us with reference data, even if the data has certain limitations and is too ideal. But it allows us to gain a deeper understanding of the overall performance and characteristics of the Clark–YH, which can provide constructive influence on our subsequent design proposals.

### *2.2. Second-generation: NACA 0012 airfoil*

The NACA 0012 airfoil is a typical symmetrical airfoil in second-generation with horizontal mean camber line and relative thickness of 12%. Compared with the first-generation, the second-generation airfoil can achieve a cruising speed exceeding the speed of sound. The F-86 is capable of supersonic speed which dives to achieve supersonic speed, and then it can maintain supersonic cruise. This is the first fighter that can fly at supersonic speed. The airfoil is designed with less thickness and less curvature of the surface curve, so it is less affected by shock wave drag at supersonic speeds. The round head is beneficial to avoid the occurrence of head separation zone and the loss of suction peak at the head, so as to improve the lift drag ratio of the aircraft. Airfoils are often cut in two-dimensional sections to study aerodynamics and to evaluate air forces or surface pressure in practical applications [3]. The shape of the NACA 0012 airfoil is shown in the Figure 2.

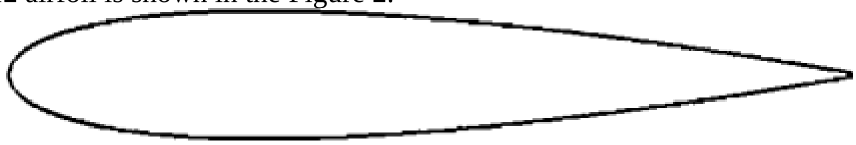

**Figure 2.** NACA 0012 airfoil.

Yannick D. Mayer’s group conducted research on larger scale of angles of attack and Reynolds numbers conditions where air flow is separated from the NACA 0012 airfoil, which has an impact on aerodynamics and acoustic properties. Stall characteristics of the airfoil as the angle of attack increases are drawn in Figure 3. When α is bigger than 9°, the absolute values of adverse pressure coefficient are significantly greater than normal conditions. When α= 15°, the pressure coefficient from the separation position to the tailing edge remains almost -1 after separation and the boundary layer is next to the leading edge after separation, which means that the NACA 0012 airfoil loses lift due to leading edge stall [4].

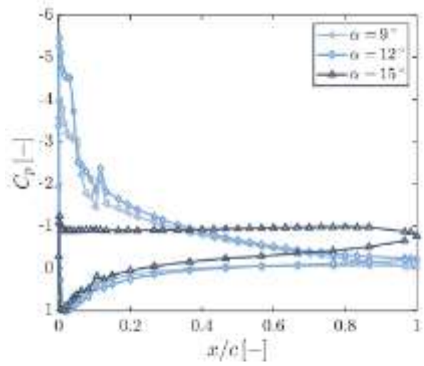


**Figure 3**. Static pressure distribution of attack at $Re_c = 3.6 \cdot 10^5$ 9° to 15° [4].

The second-generation airfoil is very suitable for studying the transonic stall characteristics and supersonic performance due to its symmetrical shape and supersonic speed. At the same time, the airfoil thickness is usually less than 6% to minimize shock drag. This generation has a higher maximum lift coefficient and a lower drag coefficient compared with the previous generation.

*2.3. Third-generation: NACA 0006 airfoil*

The F-4 maybe is the iconic of the third-generation group with NACA-type airfoil (Figure 4 & 5). Take the airfoil root of the F-4 as an example, NACA 0006.4-64 (root), which is the modified airfoil of the NACA 0006 airfoil as the prototype. This airfoil keeps the radius of leading edge unchanged, and the maximum thickness position is modified from the original 30% chord length to 40% chord length, and the maximum thickness is modified to 6.4% chord length.

**Figure 4.** NACA 0006.4-64 (root) [5].

**Figure 5.** NACA0003-64 (tip) [5].

Compared with the previous generation of airfoils, this airfoil mainly emphasizes supersonic performance, and it is very important to further reduce shock wave resistance, so the relative thickness of the airfoil will be smaller. Because wing camber does not contribute to lift at supersonic speeds, a symmetrical airfoil with zero camber is used. But the disadvantage is also obvious. At transonic speed, the drag will increase sharply with the increase of the angle of attack, reducing the flight performance [5].

*2.4. Fourth-generation: NACA 64A204 airfoil*

Compared with the third-generation fighter, which pursues speed excessively, the fourth-generation fighter shifts its research and development center to supersonic flight performance. Therefore, a number of new airfoil types led by the NACA-type wings assembled by the F-16 fighter appear. The NACA 64A204 airfoil is a great success in fourth-generation types. In order to break through the large resistance caused by the sound barrier, the leading edge of the NACA 64A204 airfoil is slightly sharp in design, and the relative thickness is 4%, as shown in the Figure 6. The design lift coefficient is 0.2, and the minimum pressure position under zero lift is 0.4 of the thickness distribution. When the speed of aircraft exceeds the critical Mach number, there will be shock waves and the resistance will increase sharply with the lift drag ecoefficiency changing greatly. Therefore, increasing the critical Mach number of NACA 64A204 airfoil can make the aircraft fly at a higher speed.

**Figure 6.** NACA 64A204 airfoil.

Fatma Zulal Kumser's group used panel method to analyze and study the aerodynamic performance of aircraft model similar to the F-16 with NACA 64A204 airfoil, under different ranges of Mach number and angles of attack, in which condition a fast prediction relationship between weight and lift coefficient is provided, enhanced using more data [6]. In order to determine NACA 64A204 airfoil's effect in practical supersonic applications, the computational fluid dynamics and Reynolds averaged Navier–Stokes are usually used [7]. Compared with the previous generation, this airfoil reduces the supersonic shock resistance. In addition to reducing the supersonic shock resistance, the research and development of airfoils also include the transonic shock buffet. Nicholas F. Giannelis' group did research on the buffet response to search for a control method in transonic shock buffet on aircraft. They found if the driving frequency is lower than the buffet, it will amplify the aerodynamic response of NACA 64A204 airfoil, and if the driving frequency is higher than the buffet, the response will be weakened [8]. In order to improve the maneuverability at high angle of attack at transonic speed, the airfoil will be modified by a certain small angle bending to reduce the resistance at high angle of attack.

*2.5. The fifth-generation: modern advanced airfoil*

The fifth-generation fighter, namely stealth fighter, meets the "4S" standard: super maneuverability, super stealth, supersonic cruise, and over-the-horizon strike. In addition, powerful information operations and battlefield perception capabilities are its necessary conditions, with representing aircrafts the F-22 and the F-35. Taking into account the aerodynamic and stealth performance, the fighter will not use a single standard airfoil. The wing layout generally adopts the method of large sweep, small aspect ratio, and reducing the relative thickness of the airfoil. The F-35A's airfoil eventually adopted flat trapezoidal wing with excellent subsonic performance [9]. The refined design of airfoil is the current trend. The Navier-Stokes Simulation is used to design the multi-section airfoil optimization design for the whole aircraft configuration with comprehensive consideration of aerodynamics, stealth, electronic control, structure and other disciplines [10].

## 3. Main research methods of fighter airfoil in the 21st century

At present, the technical indicators for designing a new generation of fighter jets are getting higher and higher, and the airfoil design needs to meet the excellent aerodynamic performance under subsonic, transonic and supersonic conditions at the same time, and to achieve broadband stealth in all climates. Total range capability, supersonic cruise capability, large angle of attack lift-drag ratio, etc. are all areas that need to be considered.

*3.1. Commonly used CFD*

Fluent, CFX, XFLOW, etc. are all commonly used CFD software. CFD software is very useful and powerful in simulating the performance of fighter airfoils and is often used to study related problems.

The software divides discrete nodes, then uses different algorithms to establish discrete equations between discrete nodes, and then calculates to get the result. This can help researchers to carry out the study of some complex problems smoothly. When researching airfoils, the airfoil model is usually established first, and then the relevant parameters are set, and the aerodynamic characteristics of the airfoil can be predicted more accurately through numerical simulation, which provides an important theoretical and technical basis for subsequent research and development. Study the relationship between aerodynamic performance and Reynolds number and thickness of fighter airfoil. Advanced parameterization methods continuously propose optimization experiments that empirically accelerate optimization convergence. Mathematical equations and major algorithms are continuously applied, and new methods are used for challenging real-world problems in aviation [11-14]. Since the result calculated by the software is only affected by parameters and algorithms, and has its own correction algorithm, it will lose reliability if it loses the support of actual experimental data.

### *3.2. Wind tunnel test*

Wind tunnel testing and CFD complement each other. The design of modern aircraft is very dependent on the wind tunnel. The aerodynamic layout of the aircraft is determined and its aerodynamic performance is evaluated through wind tunnel tests. Large fighters are often scaled down for wind tunnel testing.

### *3.3. The Navier-Stokes equations, Large Eddy Simulation and Direct Numerical Simulation*

The Navier-Stokes equations are at the heart of fluid flow modeling, the equations used to describe the motion of fluids. The Navier-Stokes equation has different formula models under different air flow regimes, which can be measured and calculated without affecting the fluid. Because fighter jets must not only fly efficiently, but also fly stably and reliably, the Navier-Stokes equations offer the possibility of progressive changes in airfoils, such as the optimal design of multi-profile airfoils for the full-body configuration [10,15]. Navier-Stokes equations, Large Eddy Simulation and Direct Numerical Simulation are constantly evolving to cope with increasingly complex environments.

## 4. Fighter airfoil development and challenges in the future

The next generation and future fighter jets will have more stringent performance requirements, which will bring new challenges to airfoil research. At the same time, the breakthrough of Navier-Stokes research, the gradual maturation and application of methods such as Large Eddy Simulation and Direct Numerical Simulation, the development of supercomputers, and the advancement of refined design technology, these changes will bring opportunities and challenges for future airfoils.

### *4.1. Stealth*

Stealth technology is constantly developing. Philip Ball once proposed to study the stealth phenomenon of the resonance absorption of sonar by moth chest scales [16]. In order to reduce the radar cross section (RSC), the airfoil will use coating materials such as titanium silicon carbide to absorb radar waves and convert them into heat, and will reduce the overall volume in design to reduce the area that can be detected by radar. In addition, more curved surfaces will be used in the design. This design is to change the direction of the radar wave and has excellent stealth effect.

### *4.2. Airfoil and fuselage are highly integrated*

The high fusion of airfoils and fuselage is one of the important development trends of next-generation fighter jets, which can greatly improve the supersonic performance and electromagnetic stealth characteristics (Figure 7). Boeing's next-generation fighter concept program highlights omnidirectional stealth [17]. This significantly reduces the radar reflection cross-sectional area of the aircraft, and can also reduce adverse airflow interference from the wings, improving the aerodynamic efficiency of the entire aircraft. However, the performance mapping relationship from the 2D profile to the 3D configuration is more complicated, and the current software simulation is not accurate enough.

**Figure 7.** Conceptual sketch of the next generation fighter announced by Boeing [17].

### *4.3. Morphing*

Morphing is a technology that can change the airfoil shape to improve aerodynamic performance to suit different flight environments. The morphing aircraft needs to change the configuration according to different flight states to adapt to the requirements, so its design needs to consider multiple disciplines and is very complex. Morphing applications are often related to aeroelastic stability and aeroelastic Control. There is room for improvement in the sensitivity of the aeroelastic behavior of morphing airfoils to the type of drive system [18].

## 5. Conclusion

This paper describes the airfoil shape characteristics, aerodynamic performance and changing trends of the first-generation fighters to the fifth-generation fighters. Future fighters will greatly develop in aerodynamic performance, stealth performance, mechanical stress structure, material technology and morphing technology. The development of CFD and the application of Navier-Stokes equations will greatly promote the development of sixth-generation fighters. Symmetrical thin airfoils can effectively reduce shock resistance at supersonic speeds, which is one of the focuses of future fighter development. The future development direction of the airfoil obtained in this paper is based on the typical fighters of the first to fifth generations, so it has certain limitations. However, it is still helpful to form a systematic view on the development history of the fighter airfoils of five generations. The future development of fighter airfoils can be predicted according to the current development of fighter airfoils, and then the requirements of a new generation fighter airfoil can be designed.

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