The improvement of fuel economy of planes by improving wing airfoils

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Abstract. This paper explains how plane designers improve the fuel economy of planes by improving the wing airfoils. This article describes three stages of wing airfoil designs. They are periods: the period between World War One and World War Two, the 1980s, and 2000s. Every time stage there is a specific kind of airfoil design to reduce the air resistance and improve fuel economy. In the end, it also gives some suggestions about future airfoil designs to improve the future fuel economy of planes.

Keywords: Fuel economy, airfoil, wingtip winglet, air resistance.

1. Introduction

Since the invention of the airplane by the Wright brothers in the United States in 1903, the wing shape of airplanes has been constantly changing. In the early days of aircraft design, aircraft were made of wood and fabric, and the main structure was a biplane structure that was relatively stable at the time. Then the all-metal fuselage was born, and the single wing completely replaced the double wing. Early piston aircraft used straight wings with the wings generally perpendicular to the fuselage. In the era of jet aircraft, the backwards-sloping swept wing structure became the mainstream of aircraft design. Today, most civil aviation aircraft use a swept-wing layout. The airfoil is more complex, mainly referring to the shape of the cross-section of the aircraft. From early wind tunnel tests to later data analysis with the help of computers, scientists are gradually optimizing the airfoil to reduce drag [1]. For civil aviation aircraft, the primary indicator is fuel economy. On an airplane, fuel economy refers to the ability to continue cruising with as little fuel consumption as possible. For civil aviation companies, passenger aircraft with good fuel economy can help them reduce fuel consumption, reduce operating costs, and increase profitability [2]. There are many aspects to reducing fuel consumption, such as improvements in engine structures and improvements in aircraft wings. This paper will conduct research and discussion from the perspective of aircraft wing airfoils, outline several popular civil aviation aircraft wing structures in different eras, and explore how they reduce aircraft drag and thereby improve fuel economy.

2. Airfoil Development

2.1. Monoplane structure of piston airliners

Before World War II, airliners all used piston propeller engines with flat wings. The Wright Brothers just invented the airplane as well as World War I, most of the airplanes used were biplane structures, because at that time airplanes were made of wood and fabric, and the monoplane structure was too fragile and may lead to the disintegration of the aircraft. At this time, the aircraft design was not too much to introduce the theory of aerodynamics, until after World War I, the birth of the all-metal fuselage, the aircraft fuselage strength was guaranteed, so aeroplanes began to transition to a monoplane structure from the original biplane and even the triplane to the monoplane. The monoplane structure has many advantages. Due to the smaller windward area and the absence of the crossbars used to hold the two wings in a biplane, the drag of the airplane is significantly reduced. At the same time, it has been found that, in addition to frictional drag, the airplane also has induced drag due to lift, differential pressure drags, etc. By utilizing a large aspect ratio wing, the induced drag can be reduced, and the effect of wingtip vortices can be mitigated. As a result, the aircraft's aspect ratio has been increasing, and it can reduce the drag, reduce fuel consumption, and improve fuel economy. The most revolutionary airliner of the period was the DC-3, designed and built by Douglas Corporation, along with its military version, the C-47. The two versions were produced in a total of 16,049 aircraft. The DC-3 was characterized by the integration of more advanced designs of the piston airliners of the time, a longer range, and a higher level of comfort, which made it popular with airlines at the time. In general, however, the fuel consumption of piston airliners was not very high, and air travel, in general, was a luxury at the time, so aircraft manufacturers did not design them with fuel economy in mind, which became important after the 1970s.

2.2. The Birth of the Wingtip Winglet

In the 1960s, aircraft manufacturers generally did not optimize airliner fuel economy due to low fuel prices, but by 1973, the outbreak of the first oil crisis led to skyrocketing oil prices and serious damage to the aviation industry. After that, all airliner manufacturers and airlines turned their focus on how to reduce fuel consumption of airliners to improve fuel economy and reduce operating costs. One of the ways to reduce fuel consumption by changing the shape of the wing is to install wingtips at the end of the wing. The winglet was invented by R.T. Whitcomb of NASA Ames Research Center in the 1970s [3]. The researcher found that winglets reduce the aircraft's induced drag by dissipating the wingtip vortices, improve the aircraft's lift-to-drag ratio, and effectively reduce the fuel consumption and exhaust emissions; therefore, the winglets reduce the emissions of pollutant gases from the aircraft and at the same time enhance the aircraft's economy, which can reduce the aircraft's operating costs for airlines to gain a competitive advantage [4]. According to the experiment, there could be a 20% decrease in induced drag at high cruising speeds [5]. Winglets can reduce lift-induced drag by changing the number of vortices and vortex distribution at the wingtip. The lift-induced drag is a by-product of downwash which dissipates momentum to the air, resulting in a lifting force. Due to this three-dimensional effect, there is a deviation from Prandtl's optimum elliptical lift distribution. Thus, the wing region at the tip does not generate much lift, and the total lift will be reduced [6]. To restore the lift, planes have to use more fuel. For this reason, wingtip can help improve this condition. After installing a winglet at the end of the wing, it can firstly play the role of blocking the airflow from the lower surface of the wing to the upper surface (generally known as the “end plate effect”), which also weakens the strength of the wingtip vortex and the tail vortex and increases the lift in the wingtip area and reduces the induced drag. Theoretically, if the lift of a plane wing is elliptically distributed, the vortex effect along the wing spread is the smallest, which is the most favorable to the induced drag, and the wingtip winglets can also improve the lift distribution along the wing spread, which can further reduce the induced drag. Most of the airliners in the 1980s began to install a variety of wingtip winglets, with various kinds of wingtip winglets including the trapezoidal wingtip winglets, fusion wingtip winglets, blade winglets, etc. A well-known example is the Boeing 747-400, which first flew in 1988. It was the first aircraft in the Boeing 747 series to be fitted with winglets and adopted the trapezoidal winglets, which increased its range by 3.5% compared to the B747-300 and significantly improved its fuel efficiency [3].

2.3. Wing design for the new century

Entering the 21st century, airliner design has entered a whole new phase. Designers have not only optimized the wing shape of airliners but also improved the fuel economy of the aircraft through the extensive use of composite materials to manufacture wings. The most important composites are carbon fibers and organic resins, which significantly reduce the mass of airliners while achieving the same strength as conventional aluminum alloys. At the same time, these composites can help designers realize several different wing shapes that can further improve fuel economy. The most iconic of the new century's airliners is the American Boeing 787. The Boeing 787 has been called a green airliner because of its many designs that greatly reduce greenhouse gas emissions, including several wing optimizations, such as Smooth Wing Technology [7]. In the 787's trailing-edge flaps, the flap guide fairings are much smaller than those of a conventional aircraft, and as a result, the 787 achieves a highly efficient lift-to-drag ratio, which in turn reduces fuel consumption and costs. In addition, there is trailing edge variable curvature control technology: the improvement of the trailing edge device and spoiler based on the 787 also realized the cruise trailing edge device variable curvature control this technological advancement, the trailing edge of the wing up and down adjustment, continue to optimize the wing shape and efficiency, to minimize fuel consumption [7]. The Boeing 787 also uses a new winglet design called the slash-cut winglet. The sloped winglet is the result of an integrated design of the wing and the winglet, which allows the wing to be sloped at a larger angle at the tip, making it technically part of the wing. This sloping wingtip helps to shorten the taxiing distance on the runway during takeoff, improving climb performance and reducing fuel consumption. Better climb performance also means less noise, which reduces the impact on the surrounding environment. According to NASA and Boeing calculations, the addition of a mitered winglet can reduce flight drag by 5.5%, which is a 3.5 to 4.5 percentage point improvement over the addition of a conventional winglet [3]. At the same time, composites make up an unprecedented 50 per cent of the total material for the entire airplane. The multiple designs have significantly improved the fuel economy of the Boeing 787, thus making it popular with airlines [7].

3. Conclusion

In general, to improve fuel economy, improvements in airliner airfoils are mainly focused on reducing the effect of vortices on the lift generated, as well as minimizing the frictional resistance in flight and improving fuel efficiency. Since the invention of the airplane in 1903, many ways have been explored and significant improvements in fuel efficiency have been made. But so far, airliner manufacturers have remained confined to the traditional “two buckets and a stick” aircraft structure, with all improvements limited to retaining the original structure and making only minor enhancements to the original framework. Therefore, in the future, will there be a new wing design that breaks away from the traditional airplane design structure and becomes practical while improving fuel efficiency, replacing today's dominant airplane structure? Perhaps this is what today's or tomorrow's aircraft designers should consider about breaking away from the traditional concepts and creating a completely different aircraft design structure, rather than just a minor wing modification.

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