Exploring Airfoil Designs for Flight Efficiency Optimization of a Subsonic Cruise Missile

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Abstract

The main purpose of determining the best airfoil design for flight efficiency is to reduce fuel consumption, therefore reducing environmental impact of fuel emissions. Many factors influence flight efficiency, the amount of energy an aircraft can endure per unit energy of fuel it consumes, but the most important one is the geometry and design of the wing. Without an appropriate wing design, the aircraft will not function optimally, meaning more fuel will be wasted to make up for the decrease in flight efficiency. Thus, it is crucial to account for multiple variables such as flight altitude, weather, weight of the vehicle, etc. to design a wing that will generate as much lift as possible while reducing drag. Current models of a Tomahawk missile will be utilized to deduce different airfoil designs which could improve flight efficiency, thereby lowering the impact of emissions on the environment as well as improving cost-effectiveness. Variations in the airfoil will be investigated using the computational fluid dynamics tool, XFLR5, and analyzed by controlling for the angle of attack, flight altitude, and subsonic speed of the missile, to determine the impact these changes have on flight efficiency.

Introduction

Lift is generated by the separation of airflow around the wing, resulting in a higher pressure pushing upward from underneath the bottom surface of the wing. The most efficient wing design can be determined using flight analysis programs which calculate how much lift versus drag is generated. Since the Tomahawk missile is a subsonic, cruise missile that is launched in the air via a vertical launch system, the wings are generally short and stubby, since the missile only becomes reliant on the lift generated by the wings once it has reached cruising altitude. This greatly reduces the complexity of the calculations for the wing, since they are not required to lift the missile off the ground. Therefore, only the cruising speed and altitude of the missile will be considered in calculations for lift.

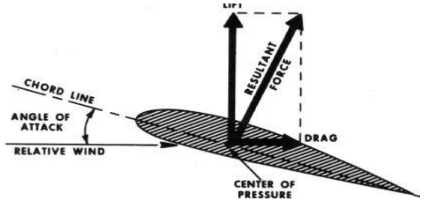

Fig. 1 Diagram of forces on a wing

Methods

XFLR5 is a useful tool that can conduct an in-flight analysis of subsonic aircraft given the flight characteristics, such as the speed and Reynold's number, Re, of the vehicle. Re is a dimensionless characteristic of flight found by the ratio of inertial forces to viscous forces. A batch analysis of the airfoil, NACA 009, was conducted using the range of Re numbers and degrees of angle of attack. The 3D model of the aircraft was then created to give a more in-depth, accurate calculation for the lift coefficient. This data is interpolated from the 2D analysis.

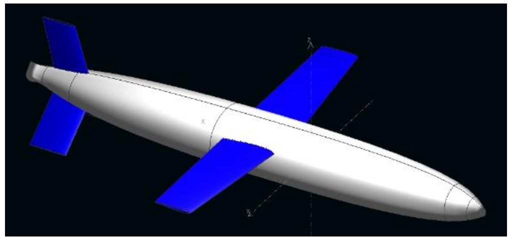

Fig. 2 3D model of the Tomahawk missile

Once the graphs for the lifting coefficient, Cl, drag coefficient, Cd, and angle of attack, α, were obtained, the optimum angle of attack was determined in order to obtain the lift coefficient for each variation. This lift coefficient was used in the lift equation, $L = C_L \rho v^2 \frac{1}{2} S$, where L is lift, ρ is density, v is velocity, and S is surface area, in order to obtain the optimal surface area for flight efficiency.

Results

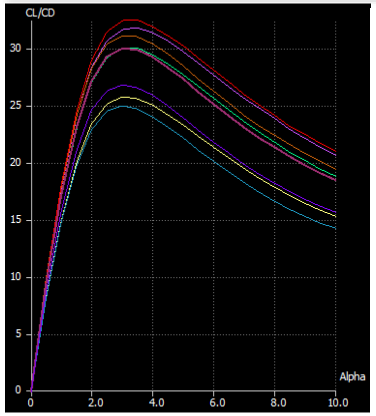

Fig. 3 Graph of Cl/Cd versus angle of attack.

Once the batch-analysis of the NACA 009 airfoil was run in XFLR5, the resulting graph was used as a reference to find the critical angle of attack, the angle of attack at which there is a maximum glide ratio, for each variation of the wing. From the graph, the variation with the highest glide ratio is the long wing, while the variation with the lowest Cl/Cd is the longer inner chord. The calculations in Table 1 show that the optimal design for this missile has a surface area of around .0561 m^2, while the flight efficiency from the wings generally decreases as the surface area increases.

Table 1: Results from flight analysis graphs

Variation	Cl/Cd	Surface Area
Tomahawk	18.45	.0591 m^2
Long Inner Chord (.3 m)	**14.16**	**.0658 m^2**
Short Inner Chord (.09 m)	20.59	.0568 m^2
Long Outer Chord (.2 m)	15.23	.0661 m^2
Short Outer Chord (.08 m)	19.35	.0572 m^2
Same Chord Length (.15 m)	18.78	.0593 m^2
Long Wing (.5 m)	**20.98**	**.0561 m^2**
Short Wing (.3 m)	15.62	.0635 m^2

Discussion

It seems that having a surface area larger than this value negatively affects the flight efficiency, since the larger surface area of the wing correlates to having a lower glide ratio. Since the missile travels at subsonic speed, it is beneficial to increase the length of the wing, as this generates more lift and the wing structure will not be compromised from external forces. However, there is a limit on how long the wingspan can be, as the longer the wingspan, the higher the risk of generating more parasitic drag. Thus, there must be a wing design that can generate as much lift as possible without compromising the structural integrity of the aircraft. In this case, a longer wing will result in an increased flight efficiency, thereby reducing the amount of fuel consumed to generate the same amount of lift.

References

1) "Tomahawk Cruise Missile." *Raytheon*, 2019, www.raytheon.com/capabilities/products/tomahawk.

2) Hall, Nancy. "The Lift Coefficient." NASA, Glenn Research Center, 2015, www.grc.nasa.gov/www/k-12/airplane/liftco.html.

3) "Glide Slope Ratio." NASA, www.nasa.gov/pdf/582952main_Glide-Slope%20Ratio%20Explanation.pdf.