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Fluid dynamics study on flight performance improvement of morphing winglets on jetliners

Jingxi Xia

University of California Irvine, Irvine, CA 92697, United States

jingxx3@uci.edu

Abstract. Winglets are structures with unique shapes designed on the wingtips of aircraft. They were first time justified as a device that can improve aircraft fuel efficiency by generating more lift in the last century and have been widely used in the aviation industry until today. The current winglets installed on jetliners, however, are fixed, resulting in that winglets can only be aerodynamically optimized for single flight condition. Searching for further improvement on flight performance, this paper investigates and analyzes two types of morphing winglets that can adjust their configurations during flight for aerodynamic optimizations under multiple conditions. Three computational studies based on three current business jets, representing aerodynamic characteristics of typical jetliners, are referenced. The studies' results are presented and categorized into different flight phases, and the flight performance is embodied in terms of aircraft maximum climb rate, lift-to-drag ratio, and cruise fuel flow rate. Finally, the overall performance gained and the feasibility of implementation are evaluated.

Keywords: Winglets, flight performance, fuel efficiency

1. Introduction

Winglets are aerodynamic structures attached to the tips of aircraft main wings. They are designed to reduce the lift-induced drag caused by the main wing, and therefore improve the aircraft flight performance. The earliest study of winglets traces back to late 19th century when British aerodynamicist Frederick W. Lanchester proposed the idea of adding vertical flat surfaces at the wingtips to reduce total drag of a wing, but the concept was not well-developed that the increased friction drag and undesired airflow around the winglets overshadowed the benefits come with it [1]. It was until the 1970s that the engineer Whitcomb at NASA Langley Research Center who performed further computational studies and wind tunnel experiments realized the concept of winglets on KC-135 (a Boeing 707 airliner converted for military use) and proved 6.5% decrease in fuel consumption, at the time when the oil prices drastically inflated [2]. Today, the incentives of less fuel consumption and less emission still present, as the International Air Transport Association (IATA) planned “Reducing the in-flight energy” as the first step from now towards the 2050 net zero carbon emission goal [3]. Currently, aircraft manufacturers from private jets to major airliners all have considered equipping winglets to improve aircrafts flight performance. For example, Boeing claims that the “Advanced Technology Winglet” on their 737 MAX series reduces fuel consumption by 1.5% and Airbus claims that the “Sharklets” on A320 NEO series brings 4% fuel consumption reduction [4, 5].

The mechanism of winglets reducing induced drag is articulated as the following. The lift of a wing is generated by the pressure difference of the air flows between the upper and lower surfaces of the wing. The high pressure is distributed below the wing and low pressure is located above the wing. Due to the finite span of a typical wing, the high-pressure air tends to flow towards the low-pressure area near the wingtips. This creates wingtip vortices at trailing edges of wingtips, where a downwash created below the wing surface and an upwash created above the wing surface. Thus, at the tip section of the wing, the local wind direction is downward deflected, causing an induced angle-of-attack, which results in an induced drag component of the lift force vector. The induced drag is the inevitable byproduct of the lift generated. However, winglets is one of strategies to alleviate the induced drag. The winglets can reduce the wingtip vortex strength by functioning as a fence at wingtips to prevent certain amount of air from escaping from the high-pressure area under the wing. Moreover, winglets with airfoil shapes utilize the local wind (sidewash) to generate lift towards fuselage and this lift vector has a forward thrust component, which can counteract part of the induced drag [6].

Hitherto, however, winglets on almost all aircrafts are fixed and cannot adapt their configurations according to different flight phases, resulting in winglets operating under non-optimal circumstances. The purpose of this passage is to explore the option of morphing winglets, which are further divided into cant angle morphing winglets and camber morphing winglets, and analyze the optimal configurations for low Mach number climb, high Mach number climb or cruise level change, and high Mach number cruise phases for civil jetliners.

2. Cant Angle Morphing Winglets

One improvement on the fixed winglet is to make the cant angle flexible. Cant angle, also known as the dihedral angle, is defined as the angle between the main axes of the main wing and winglet. Several studies have indicated the potential benefits of changing winglet cant angle in different phases in flight. This section focuses on analyzing effects of changing cant angle of the winglet on flight performance at take-off and low Mach number climb at low altitude, high Mach number climb or changing cruise level at high altitude, and finally cruise at high flight altitude.

2.1. Take-off and low Mach number climb at low altitude

In a performance research study in 2018 based on equipping cant angle morphing winglets on Cessna Citation X private business jet illustrates the optimized winglets cant angles and the increased maximum climb rate of the aircraft. The aircraft Cessna Citation X was selected because of its representative flight performance for general civil jetliners: cruise Mach number of 0.8 to 0.83 and typical cruise level of 37,000 to 45,000 feet. The group obtained aerodynamic data and engine data from the Citation X flight simulator and used Open Vehicle Sketch Pad (OpenVSP), an open-source software developed by NASA for aircraft performance study, to model the original aircraft and aircrafts with different cant angles winglets and, then, perform computational study at different flight conditions [7].

The first section of the study investigates the additional climb rate the aircraft gains with optimized winglets cant angle under various gross weights, with indicated airspeed (IAS) ranging from 150 to 250 knots, converted to Mach number between 0.2 to 0.5, under 10,000 feet altitude, which resembles the take-off and initial climb phases. By analyzing 405 climbing conditions, the results indicate that when aircraft take-off and climb with between 33,000 and 35,000 pounds of gross weight, 19.2 to 25 feet per minute higher climb rate can be gained, comparing to the original Cessna Citation X without winglets installed, by setting winglets cant angles from 10 to 20 degrees [7].

2.2. High Mach number climb or changing cruise level at high altitude

The second part of the study on Cessna Citation X mentioned above focuses on the climb rate the aircraft gains with optimized winglets cant angle under gross weights 27,000 to 35,000 pounds, with indicated airspeed (IAS) ranging from 250 to 340 knots (Mach speed between 0.5 to 0.9) at flight altitude 10,000 feet to 30,000 feet, which resembles the high altitude climb or cruise level change phases. Within the 405 climbing conditions studied, noticeable climb rates are gained only above altitude 30,000 feet at weights closed to 35,000 pounds, where the aircraft has at most 20 feet per minute climb rate higher than the original Citation X without winglets under IAS 250 knots, and the optimal cant angles are between 20 to 80 degrees. The result does not show meaningful climb rate gain when flying at IAS 340 knots or around Mach 0.9 [7].

This result coincides with another study in 2021 on a similar type of aircraft Bombardier CRJ-700. Researchers perform Computational Fluid Dynamics (CFD) study of the aircraft with changeable cant angle winglets flying at altitude 30,000 feet, Mach 0.8, and angles of attack (AOA) of 0 and 4 degrees. It shows that under AOA of 4 degrees, which corresponds to the high Mach number climb scenario, 73 degrees of cant angle offers the aircraft the highest lift-to-drag ratio, and, thus, best high Mach climbing performance [8].

2.3. Cruise at high flight altitude

In the same study of changeable cant angle winglets on CRJ-700 as mentioned above, the case of 0 degree AOA, flight altitude 30,000 feet, and Mach 0.8, corresponds to the flight parameters when aircraft is cruising at high altitude. The result shows the 0 degree cant angle gives the aircraft highest lift-to-drag ratio [8].

In addition, similar outcome can be observed from the last part of the 2018 Cessna Citation X research, where 140 cruise conditions were analyzed, cruise altitude ranging from 10,000 feet to 45,000 feet, aircraft gross weight from 27,000 to 35,000 pounds, and three specific Mach number 0.65, 0.75, and 0.85. Although the optimal winglets cant angle that result suggests range between 0 to 80 degrees, for a typical cruise flight level of business jets and commercial airliners between 30,000-40,000 feet, the optimal cant angles for all three Mach speed are between 0 to 20 degrees. The maximum gain in flight performance, measured in cruise fuel flow rate reduction, is achieved at cruise altitude 45,000 feet, Mach 0.65, gross weight 32,000 pounds, of 20 pounds of fuel per hour comparing to the original Cessna Citation X without winglets [7].

3. Camber Morphing Winglets

The second improvement on the current fixed winglets is to make the camber of winglets airfoil flexible. The concept was initially proposed and developed by Martins and Catalano [9]. According to the concept, the section before the quarter chord ($x/c<0.25$) and that after the 3-quarter chord are adjustable according to different flight conditions. However, the leading edge, trailing edge, and the section between quarter chord and 3-quarter chord ($0.25<x/c<0.75$) of the airfoil remain fixed. This section analyzes the effects of camber morphing winglets on aircraft flight performance. Research have illustrated the improvement on airflow around winglets, resulting less intense wingtip vortex, and increase in the lift force produced by the winglets, resulting greater thrust component of the lift to counterbalance the total drag of an aircraft.

The study optimizes the camber shapes of the five sections selected on the winglets of Embraer Legacy 500 business jet under the five typical flight phases including take-off, climb, cruise, descend, and landing. The optimization and aerodynamic performance computation are done by using genetic algorithm and the BLWF code, a programing code developed by the Central Aerohydrodynamic Institute for evaluating and analyzing aerodynamic characteristics of transonic aircraft [10, 11]. Additionally, a Computational Fluid Dynamics (CFD) study is carried out by the ANSYS-CFX package using Reynolds-averaged Navier-Stokes governing equations to provide qualitive evaluations. Finally, a comparison is made between the original Legacy 500 with fixed geometry winglets (FGW) and the version with optimized camber morphing winglets (CMW) on performing a 3125 nautical miles maximum range mission.

According to the CFD study, the vorticity contours demonstrate a comparison of trailing edge and wingtip vortices strength between the FGW baseline winglet and optimized CMW winglet. Under both climb and cruise conditions, instead of two vortices developed behind the FGW baseline winglet, the optimized CMW winglet merges the vortices generated by the wing and the winglet itself and attenuates the overall strength. Moreover, the pressure coefficient curves and pressure contours calculated demonstrate the discrepancies between the FGW baseline and optimized CMW under climb and cruise phases. For both phases, the optimized CMW curves show the elongated favorable pressure distribution along the airfoil, indicating delayed flow separation on the upper surface of winglets. This phenomenon indicates the higher lift force and less pressure drag generated by the optimized CMW [12].

The quantitative research result on CMW on flight performance is presented in terms of a comparison of performing maximum range mission between FGW and CMW. The CMW has 20.9% shorter time to climb, which contributes to 17.6% less fuel consumption during climb phase, and 5.9% reduction in cruise fuel consumption, which result in 6% reduction in total mission fuel. Furthermore, it is worth noting that for the same 6.25 hours of cruise time, CMW saves 200kg of fuel, which can be converted to cruise fuel flow reduction of 70.5 pounds per hour, more than 3 times of fuel reduction comparing to the Citation X with cant angle morphing winglets [10].

4. Discussion

In the short term, cant angle morphing winglet is a more feasible implementation and improvement on current jetliners, for the following two reasons. Firstly, the research based on Cessna Citation X and CRJ-700 reveal noticeable boost in aircraft maximum climb rate, lift-to-drag ratio, and reduction in cruise fuel flow. There is no doubt that the general implementation of cant angle morphing winglet on jetliners will result in remarkable reduction in carbon emissions of the aviation industry. Secondly, the 2021 study of CRJ-700 has already proposed a comprehensive proposal in implementing the cant angle morphing winglets on CRJ-700, covering the structural design of the morphing mechanism and the in-flight control mechanism of the winglets. In fact, the Boeing newest widebody airliner Boeing 777X has already realized the folding winglets feature, though the feature is mainly designed to fit the “oversized” wingspan of 777X into current aerodromes constraints on ground operation, and has not been able to adjust cant angles during flights [13].

Camber morphing winglets possess higher potential flight performance improvement. According to the theoretical results, at cruise phase for example, it leads to more than 3 times fuel consumption reduction comparing with cant angle morphing winglets. However, the material can be used to manufacture the morphing sections of the winglet and the design of morphing actuation system on the aircraft have not proposed in the field and, thus, required further research, which make this solution more challenging in the near future.

5. Conclusion

For the sake of further improving flight performance and reducing carbon emissions in jetliners industry for the “Net Zero” goal, implementing cant angle morphing winglets and camber morphing winglets are the two strategies proposed and analyzed in this paper in replacement of current fixed winglets on jetliners. Those winglets are supposed to optimize aircraft efficiency by adjusting their configurations in different flight conditions. For cant angle morphing winglets, two computational studies based on Cessna Citation X and Bombardier CRJ-700 are referenced and winglet angle settings with performance improved is articulated during three representative flight phases: take-off and low Mach number climb at low altitude, high Mach number climb or changing cruise level at high altitude, and cruise at high flight altitude. For camber morphing winglets, the CFD study based on Embraer Legacy 500 is referenced for performance effects analysis. Based on the evaluation, cant angle morphing winglets is a more feasible option in the near future but have relatively less performance improvement while the camber morphing winglets possess greater improvement potential but further research on structural design and morphing material are still required.

References

[1] Gavrilović, Rašuo, B. P., Dulikravich, G. S., & Parezanović, V. B. (2015). Commercial aircraft performance improvement using winglets. FME Transactions, 43(1), 1–8. https://doi.org/10.5937/fmet1501001G

[2] Dunbar, B. (n.d.). NASA Dryden Technology Facts - Winglets. NASA. https://www.nasa.gov/centers/dryden/about/Organizations/Technology/Facts/TF-2004-15-DFRC.html
[3] Aircraft Technology Net zero roadmap - IATA. (n.d.). https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/aircraft-technology-net-zero-roadmap.pdf
[4] Boeing says radical new winglets on 737 MAX will save even more fuel. NYCAviation. (2012, May 2). https://www.nycaviation.com/2012/05/boeing-says-radical-new-winglets-on-737-max-will-save-more-fuel/22492
[5] A320neo. Airbus Aircraft. (2021, October 7). https://aircraft.airbus.com/en/aircraft/a320-the-most-successful-aircraft-family-ever/a320neo
[6] Guerrero, Sanguineti, M., & Wittkowski, K. (2020). Variable cant angle winglets for improvement of aircraft flight performance. Meccanica (Milan), 55(10), 1917–1947. https://doi.org/10.1007/s11012-020-01230-1
[7] Segui, M., & Botez, R. M. (2018). Cessna citation X climb and cruise performance improvement using adaptive winglet. Advanced Aircraft Efficiency in a Global Air Transport System (AEGATS), (13).
[8] MEYRAN, PAIN, H., BOTEZ, R. M., & LALIBERTÉ, J. (2021). Morphing Winglet Design for Aerodynamic Performance Optimization of the CRJ-700 Aircraft. Part 1 – Structural Design. INCAS Bulletin, 13(4), 113–128. https://doi.org/10.13111/2066-8201.2021.13.4.10
[9] Martins, A. L., & Catalano, F. M. (2003). Drag optimization for transport aircraft Mission Adaptive Wing. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 25(1), 1–8. https://doi.org/10.1590/S1678-58782003000100001
[10] Eguea, Pereira Gouveia da Silva, G., & Martini Catalano, F. (2020). Fuel efficiency improvement on a business jet using a camber morphing winglet concept. Aerospace Science and Technology, 96, 105542–. https://doi.org/10.1016/j.ast.2019.105542
[11] Zhang, & Hepperle, M. (2010). Evaluation of the BLWF Code - A Tool for the Aerodynamic Analysis of Transonic Transport Aircraft Configurations.
[12] Eguea, Bravo-Mosquera, P. D., & Catalano, F. M. (2021). Camber morphing winglet influence on aircraft drag breakdown and tip vortex structure. Aerospace Science and Technology, 119, 107148–. https://doi.org/10.1016/j.ast.2021.107148
[13] Humphries, M. (2018, May 22). FAA approves Boeing’s folding wingtips. PCMAG. https://www.pcmag.com/news/faa-approves-boeings-folding-wingtips