Flying V: An Efficient Airframe for Long-Haul Transport

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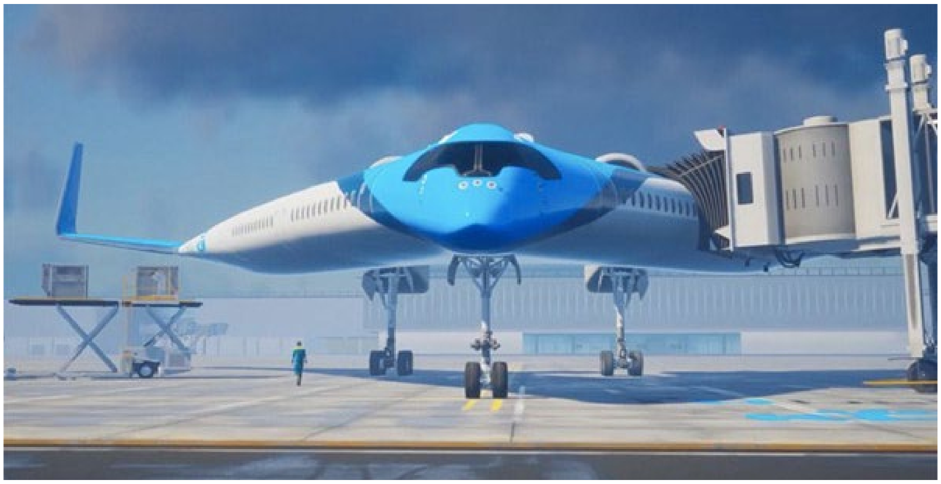

FIGURE 1: The Flying V reduces energy consumption per passenger-kilometer by 20% due to is unique shape.

Introduction

To achieve climate-neutral aviation in an affordable way, future airplanes need to consume as little energy as possible. Therefore, future airplanes need to benefit from more efficient engines while the airframes need to produce less drag. The latter can be achieved by reducing weight and improving the aerodynamic efficiency of the airplane. While improving the aerodynamic efficiency has been a priority for airframers for many years, new airframe technologies are required to make the desperately needed improvement in fuel efficiency. One example of such a new airframe is Otto Aviation's Celera 500L, a propeller-powered business aircraft for six persons with a range of 4,500 nmi. Its design features a natural laminar-flow fuselage, wing and tail. The wing has a high aspect ratio and features large winglets resulting in a glide ratio of 22.

Having the same goal as the Celera 500L, i.e. to minimize energy consumption per passenger-kilometer, a new configuration for long-haul aircraft is being thoroughly researched by Delft University of Technology. The Flying V is a flying-wing configuration designed for long-haul passenger transport (Figure 1). The passengers, cargo and fuel are located in the wing. Due to its shape, it consumes 20% less energy per passenger-kilometre than its tube-and-wing counterpart for the same top-level aircraft requirements[1]. This is caused by three factors: First, the absence of a distinct fuselage and tail reduce the wetted area by 5% leading to reduced friction drag. Secondly, the large winglets increase the effective span of the wing leading to a reduction in lift-induced drag. Finally, the lateral distribution of the payload and fuel reduce the bending moment and thereby the structural weight of the airplane. These benefits stem directly from the shape of the airplane and can be further complemented by innovations in the airframe or the propulsion system.

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[1] Oosterom, W. and Vos, R., "Conceptual Design of a Flying-V Aircraft Family," Proceedings of AIAA Aviation Forum, Chicago, Il, June 27 – July 1st, 2022.

While the Flying V is not the only innovation in airframe technology in recent years, it is radically different from anything we have seen before in civil aviation. Also, the introduction of this new airframe could result in a significant reduction in aviation emissions, as long-haul widebody aircraft have large share herein. In the subsequent paragraphs, the Flying V design is further described and the associated challenges with this new configuration are discussed.

An Efficient Use of Interior Volume

One of the key features of the Flying V is its high volume-to-wetted-area ratio. This benefit is exploited by efficiently using the available interior volume without compromising the comfort level of the passengers.

As can be seen in Figure 2, the cabin of the airplane features a 3-4-3 configuration in both legs yielding four aisles. This reduces the boarding and deboarding time.[2] A large cross aisle is present that connects the legs of the cabin with a large galley located in the middle. The door distribution is chosen such that the emergency evacuation can be ensured within 90 seconds for a high-density configuration of the cabin.[3] The cargo compartment is located behind the cabin. To allow for the cargo nets to expand during a forward deceleration of 9g, space is reserved between the cargo containers and the aft cabin wall. The cargo containers that are used are of the LD4 type and are located in a tapering part of the wing. The fuel tank is located behind the cabin in the trailing edge of the wing as well as in the wing box of the outer wing. The economy seats are rotated by 9 degrees with respect to the cabin aisles to stay within certification constraints. The business class seats have seat belts with embedded airbags. By removing wing plugs (denoted in green and yellow in Figure 2), smaller versions can be created such that a family of Flying V aircraft results.

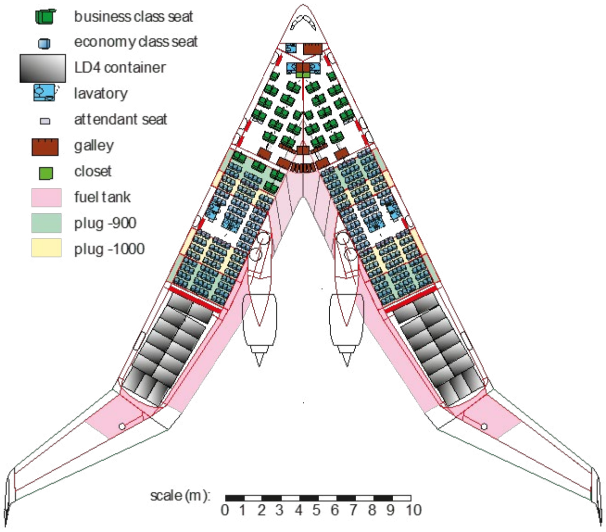

FIGURE 2: Planform view of the largest version of the Flying V configuration with 52 business class seats (55” pitch) and 309 economy class seats (32” pitch) [1].

Aerodynamics and Flight Control

The Flying V has a crescent wing planform with a 64-degree leading-edge sweep on the inner wing and a 40-degree sweep on the leading edge of the outer wing. The large inboard sweep angle allows for a cabin height of 2.1 meters without the formation of strong shock waves in the design condition.[4] The outer wing is designed as a traditional transport wing with supercritical wing sections. The low aspect ratio (around 4.5) combined with the high sweep angle result in a low lift-curve slope. Due to the large sweep angle of the inner wing, the stall of the Flying V is quite gradual with a maximum lift coefficient of around 1.[5] Depending on the Reynolds number, large vortex structures are formed beyond a critical angle of attack that result in vortex lift. Since the outboard wing stalls first, there is a risk of a strong nose-up pitching moment. Therefore, a leading-edge slat or droop nose might be necessary to ensure acceptable low-speed stall characteristics.

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[2] Isgro, F., Fuselage Design Studies to Improve Boarding Performance of Novel Passenger Aircraft, Delft University of Technology, 2020.

[3] Gebauer, J. and Benad, J., ``Flying V and Reference Aircraft Evacuation Simulation and Comparison,” www.researchgate.net/publication/349309406_Flying_V_and_Reference_Aircraft_Evacuation_Simulation_and_Comparison, accessed 30 March 2022.

[4] Faggiano, F., Vos, R., Baan, M. and van Dijk, R., Aerodynamic Design of a Flying-V Aircraft, in 17th AIAA Aviation Technology, Integration, and Operations, Denver, Colorado, 2017.

[5] Palermo, M. and Vos, R., Experimental Aerodynamic Analysis of a 4.6%-Scale Flying-V Subsonic Transport, in AIAA SciTech 2020 Forum, Orlando, FL, 2020.

FIGURE 3: Large vortex structures appear at high angles of attack over the inner wing of the Flying V.[6]

FIGURE 4: Flight control was experimentally verified using a 5%-scale flight-test demonstrator. Photo: Joep van Oppen for KLM and TU Delft

The outer wing features various types of control surfaces. The most outboard control surfaces on the wing are multifunctional. They act as drag rudders as well as elevons. Together with the "normal" rudders on the large winglets, they provide sufficient yawing moment to control the aircraft in a one-engine-inoperative condition.[7] The inner two control surfaces act as elevons controlling both pitch and roll. Secondary flight control surfaces in the form of spoilers are added on the inboard and outboard side of the engine. They ensure that 20% of the lift can be dumped upon landing. To ensure adequate flying and handling characteristics the airplane is statically stable in pitch, roll and yaw. With the addition of a simple yaw damper and auto-throttle also dynamic stability is ensured in all modes (see Figure 4). However, due to the absence of a tail a strong coupling between the pitching and heaving movement is experienced which warrants the introduction of dedicated flight control laws for this configuration.[8]

Flight Performance

While the flight performance during climb, cruise and descent are not notably different from a tube-and-wing aircraft, the take-off and landing characteristics are quite different. Due to the low lift-curve slope of the wing, the airplane has a maximal approach attitude of 14 degrees. Note that the airplane does not feature any trailing-edge flaps to reduce its landing attitude. To allow the airplane to have sufficient clearance at the tip during an 8-degree banked landing, large landing-gear legs are required and perhaps even an outrigger wheel (see Figure 2). However, operational constraints place the maximum height of the cargo door at 5.5 meters when the airplane is completely empty. To stow the main landing gear efficiently in the wing, a double hinged mechanism is required.[9] Furthermore, for a maximal approach speed of 140kts at the maximum landing weight, an overnose angle of 31 degrees is required to satisfy certification constraints on pilot visibility.[10] This drives the shape of the cockpit, which is further complicated by the stowage of the nose wheel combined with the relatively low height of the fuselage.

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[6] Viet, R., Analysis of the flight characteristics of a highly swept cranked flying wing by means of an experimental test, Delft University of Technology, Delft, 2019.

[7] Cappuyns, T., Handling Qualities of a Flying V Configuration, Delft University of Technology, Delft, 2019

[8] Garcia, R., Vos, R. and de Visser, C., Aerodynamic Model Identification of the Flying V from Wind Tunnel Data, in AIAA Aviation 2020 Forum, Virtual Event, 2020

[9] Bourget, G., The effect of landing gear implementation on Flying V aerodynamics, stability, and controllability. Delft University of Technology, Delft, 2020.

[10] Van der Pluijm, R., Cockpit Design and Integration into the Flying V, Delft University of Technology, Delft, 2021.

The Next Three Years

Research on the Flying V is still relatively recent, and it is still to be confirmed whether this configuration can meet all the certification requirements, while still achieving the improvement in payload-range efficiency. Therefore, multiple studies are currently ongoing to prove that this design can successfully replace widebody aircraft in the future. Active areas of research performed at Delft University of Technology, in conjunction with partners such as KLM and Airbus GmbH, include noise assessment, engine integration, landing gear integration, aerodynamic design, aeroservoelasticity, flight control, and climate impact assessment.