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# THE FLYING V
## A NEW AIRCRAFT CONFIGURATION FOR COMMERCIAL PASSENGER TRANSPORT

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**Abstract**

In this work an idea on how to efficiently use the volume inside a pure flying wing for commercial passenger transport was derived and a configuration proposal was made with this idea. This configuration was then compared with a reference aircraft. The idea is to arrange two cylindrical pressurized sections for the payload swept back in the shape of a V and place them inside the front section of a wing with the same sweep angle. The streamwise cut through the oblique pressurized section is flat and elliptical and thus, it fits efficiently into conventional airfoils. The cut of the pressurized section orthogonal to the leading edge however, is circular. This leads to an efficient structural solution as pressure can be preserved well in a cylindrical shape. The proposed configuration is called the Flying V. For this configuration transition and outer wings extend the span of the highly swept middle wing at a lower sweep angle to 65m. The Flying V was designed in this work with a capacity of 315 passengers in a two class layout for a cruise speed of Ma=0.85. The Airbus A350-900 has the same capacity and cruise speed and was chosen as a reference aircraft. Preliminary estimations made in this work indicate that the Flying V might have a benefit over the reference in terms of aerodynamics (10% higher L/D) and mass (2% lower empty weight). More qualitative arguments in favor of the Flying V which could be derived are the compactness and simplicity of the configuration (less parts, no high-lift devices, no fairings, straight lines) and the shielding of the engines from the ground (low noise). Remarkable is also the elliptical lift distribution of the naturally stable design using only a moderate wing twist and no reflexed camber lines. A radio controlled model of the Flying V was presented in this work to demonstrate these aerodynamic characteristics and support the estimations and simulations which were made.

## 1. INTRODUCTION

The goal of this work was to design a commercial passenger aircraft as a flying wing.

A flying wing shall be defined as a flying object heavier then air with no more than one lifting surface in the direction of flight in the scope of this work. A pure flying wing shall be defined as a flying wing with no extra fuselage exposed to the outside.

The work was a three step process.

First, the state of the art of commercial passenger aircraft as well as the historic development and the flight physics of flying wings were researched.

Second, a new concept was generated.

Third, this concept was compared with a reference.

## 2. STATE OF THE ART

For most of today's aircraft, a pipe like fuselage accommodates the payload (see FIGURE 1). Generally, its cross section is circular. This way, internal pressure loads the structure with tension rather than bending and is thus preserved with a minimum of structural mass. Wings attached to the fuselage generate the necessary lift, which is proportional to the square of the aircraft's speed and the wing area. The aircrafts drag increases with the wetted area and decreases with the wingspan at constant lift. [1,2]

In order to minimize the wetted area, the wing area is kept low. This results, however, in the need to modify the shape of the wing at take-off and landing using high lift devices so that enough lift can be generated at such low speeds. High lift devices create large nose down pitching moments and thus, they generally set the size for the horizontal tailplane, which is commonly located at the fuselage aft section. As wings are nothing more than line loaded cantilever beams, their weight increases with higher wingspan. The thrust is provided by engines which are attached to the wing or the fuselage. Mounting the engines at the wing decreases the wing bending moments and therefore the airplanes mass. However, a large vertical tailplane is then needed for the case of an engine failure. When the engines are attached to the fuselage, the vertical tailplane is smaller but the mass of the wings increases. [1,2]

FIGURE 1. A state of the art commercial passenger aircraft, the Airbus A350-900. [3]

## 3. FLYING WINGS

The first flying wings may have been animals which are believed to have sored the skies long before humans set foot on the earth. The Quetzalcoatlus for instance, was a giant reptile with only one lifting surface in the direction of flight. It is believed to have flown 70 million years ago. [4]

The first men-made flying wing which could make several free, controlled and stable flights was built by Igo Etrich. He designed a glider after the seed of the Alsomitra Macrocarpa plant which grows in the tropical Asian forests of the Malay Archipelago and the Indonesian islands. [5,6]

Many more pioneers built flying wings, one of their main design challenges being the stability of their aircrafts. Jose Weiss was one of the first to mention wing twist as a measure for stability which he demonstrated with his flying glider "Olive" in 1909. John Dunne started to build several different flying wing biplane configurations with swept and twisted wings in 1911. [7]

Alexander Lippisch as well as Walter and Reimar Horten refined the geometry of flying wings and improved their aerodynamics to meet the performance of other aircraft of the time in the following years. Lippisch gained much experience with a variety of glider configurations, built the first delta wings, and in 1940 he proved that a conventional design without a horizontal tail can be a successful aircraft: More than 350 airplanes of the Messerschmitt Me 163 were built. [7]

With today's knowledge, the stability of flying wings is no longer one of the major issues. Leaving away the horizontal tail creates a variety of advantages and disadvantages and only a holistic approach to the design problem can give an answer if the flying wing design should indeed be chosen for the given boundary conditions. Especially military airplanes are often designed as flying wings. Two prominent examples from the Cold War are the F7U Cutlass and the Vulcan Bomber. The only commercial passenger aircrafts designed as a flying wing were the Aérospatiale-BAC Concorde and the Tupolew Tu-144. Today, many fighter aircraft are designed as flying wings and the B2 is a very well-known example of a pure flying wing bomber. Recently, also many military drones have been designed as flying wings. However, the pure flying wing commercial passenger aircraft has not been realized so far.

Two of the main requirements for static flight of flying wings (and other aircraft) are, that forces and moments which act on the aircraft are in equilibrium

(1) $$\sum \underline{F}_i = 0 \text{ and } \sum \underline{M}_i = 0,$$

and that the aircraft must be longitudinally stable, so has to return to its equilibrium position after a disturbance. For natural longitudinal stability, the center of gravity has to be placed in front of the aircrafts neutral point (see FIGURE 2).

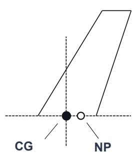


FIGURE 2. One half of a swept wing seen from above – for natural longitudinal stability, the center of gravity of the aircraft must be placed in front of its neutral point

## 4. REQUIREMENTS FOR THE AIRCRAFT TO BE DESIGNED

The following constraints were set for the aircraft to be designed:

- Pressurized passenger and cargo section available
- Level of comfort must be as high as in existing configurations
- Aircraft must be possible to trim, aircraft must be longitudinally stable
- Fast emergency evacuation must be possible
- Aircraft must be able to take-off and land at existing airports
- Aircraft must be compatible with the ground infrastructure of existing airports

Efficiency was quantified with Breguet's formula [1]:

(2) $$\frac{ds}{dm} = \frac{a \cdot Ma \cdot L/D}{sfc \cdot m \cdot g}$$

Therein ds/dm is the distance the aircraft can momentarily travel with a unit of fuel, a is the speed of sound, Ma is the aircraft's Mach number, L/D is the aircraft's lift to drag ratio, sfc is the specific fuel consumption of the engines, m is the aircraft's mass and g is earth's gravity.

The goal of the design work was declared to be the following:

A configuration for a flying wing commercial passenger aircraft shall be found which does not violate the constraints above and has a mass as low as possible and an L/D as high as possible for a given number of passengers.

## 5. THE TRAIN OF THOUGHT LEADING TOWARDS THE FLYING V

From the set goals, certain design features were derived:

To achieve a low mass:
- Almost circular cabin cross section
- Almost elliptical spanwise mass distribution

To achieve a high L/D:
- Low wetted area, high wing span, elliptical lift distribution
- Engines close to center axis
- Low transonic drag
- Short cabin length in flight direction, fuel tanks evenly distributed around the center of gravity, long lever arm of control surfaces to the center of gravity

Others:
- Enough wing area to not need high lift devices
- Shielding of the engines from the ground
- Simple and straight lines, few moving parts

This points lead to the following configuration:

Two cylindrical pressurized sections for the payload are swept back in the shape of a V and placed inside the front section of a wing with the same sweep angle (see FIGURE 3).

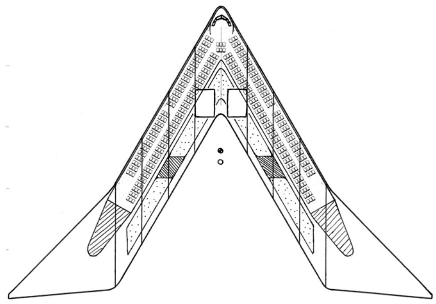

FIGURE 3. First sketch of the configuration

The streamwise cut through the oblique pressurized section is flat and elliptical and thus, it fits efficiently into conventional airfoils (see FIGURE 4). The cut of the pressurized section orthogonal to the leading edge however, is circular. This leads to an efficient structural solution as pressure can be preserved well in a cylindrical shape.

FIGURE 4. Efficient use of space with a cylindrical pressurized section which cuts through the plane of the airfoil in the shape of an ellipse

The proposed configuration is called the Flying V. For this configuration (see FIGURE 5 and FIGURE 6) transition and outer wings extend the span of the highly swept middle wing at a lower sweep angle to 65m. In a two class layout it has a capacity of 315 passengers.

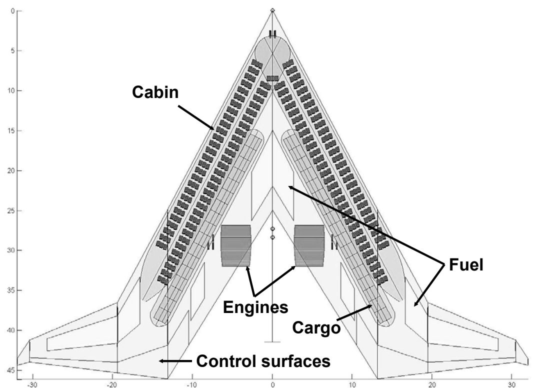


FIGURE 5. Concept of the Flying V aircraft configuration

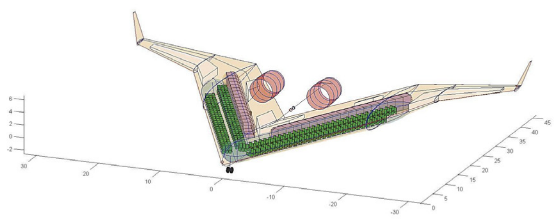

FIGURE 6. 3D view of the Flying V aircraft configuration concept

Seats of the configuration may be turned relative to the cabin to point into the flight direction.

## 6. PRELIMINARY DESIGN OF THE FLYING V

Aerodynamics and mass of the Flying V aircraft configuration and a reference aircraft were assessed in order to determine if the Flying V aircraft configuration may have a benefit over the conventional configuration. As reference aircraft the Airbus A350-900 was chosen. It has a capacity of 315 passengers in a two class layout. This roughly matches the capacity of the Flying V.

### 6.1. Aerodynamics

Both aircraft were evaluated with the same tool and then compared. Thus, a realistic comparison somewhat independent from the used tool should be achieved.

The tool used is a 3D lattice vortex method called ODILILA (see FIGURE 7) which was developed in the Future Project Office of Airbus in Hamburg.

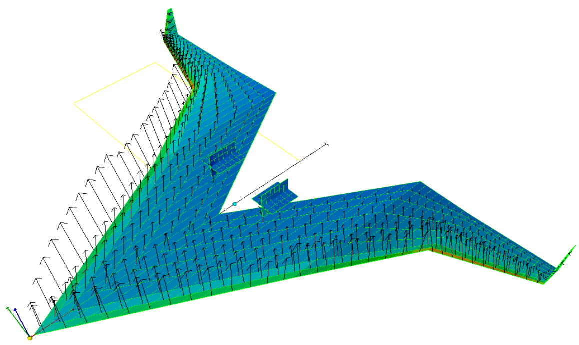

FIGURE 7. Exemplary lift distribution over the Flying V calculated with the lattice vortex method tool ODILILA

The tool was used to optimize the wing's twist for best performance at cruise flight (Ma=0.85 at FL360) and to predict drag, lift distribution and neutral point – all of these also at cruise flight and for both aircraft. These values were obtained for a cruise $C_L$ of 0.25 at 0.95*MTOW, which follows from the first rough MTOW estimate of the aircraft of 260t and a wing area of 895m$^2$.

The tool does not predict wave drag. However, relative profile thicknesses for the thick Flying V middle wing do not accede 15% and the wing loading is much lower than on the reference. Thus, it was decided to disregard the wave drag for a first preliminary estimation (for both aircraft). For the Flying V, the results for the lift distribution and the neutral point are shown in the following figures (see FIGURE 8, FIGURE 9 and FIGURE 10).

Note that the planform of the Flying V was designed in a way, that the lift distribution is almost elliptical for trimmed cruise flight and that the neutral point is behind the center of gravity, so that the design can be longitudinally stable.

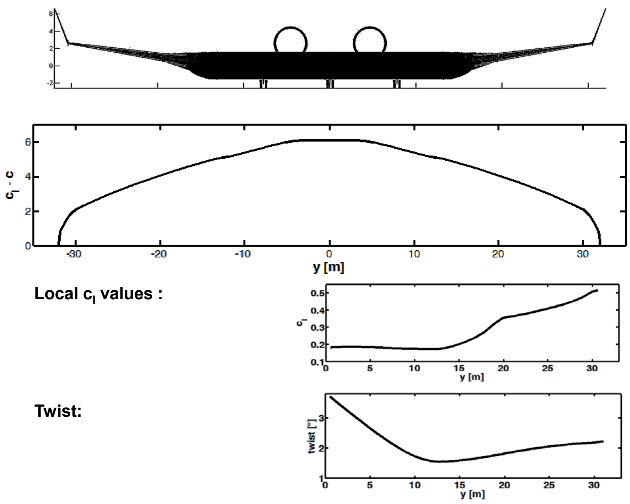


FIGURE 8. Results for the lift distribution in cruise flight as obtained with ODILILA: The first graph shows the local $c_l$ values times the local chord, the second graph shows only the local $c_l$ values for half the span, the third graph shows the wing twist over half the span.

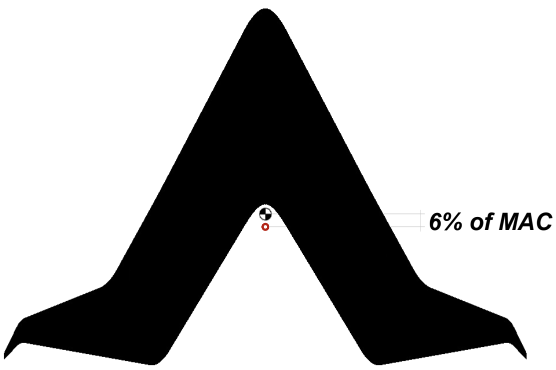


FIGURE 9. Position of the neutral point (lower dot) of the Flying V – a static margin of 6% was chosen which gives the required center of gravity position (upper dot)

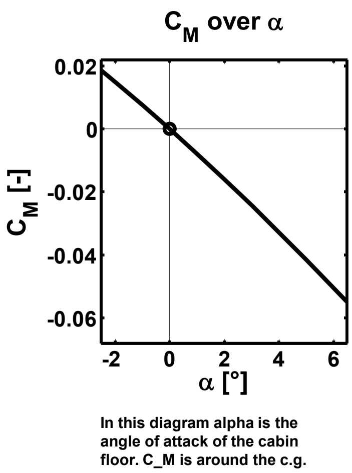


FIGURE 10. $C_M$ over the angle of attack of the cabin floor. The Flying V is longitudinal stable and trimmed for α=0°.

When the performance of Flying V and reference is compared, it seems that a benefit of the Flying V configuration might be possible (10% higher L/D) (see FIGURE 11):

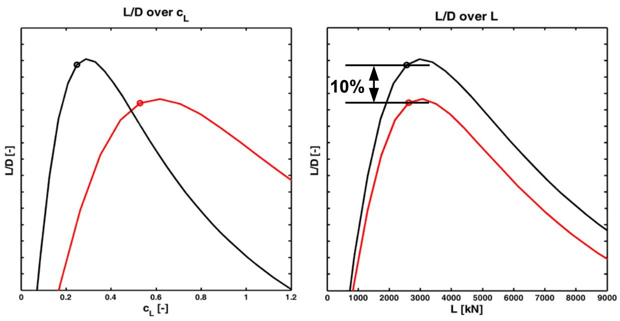


FIGURE 11. L/D[1] over $C_L$ and L, black upper line: Flying V, red lower line: A350-900, marked is the design CL and the design lift for which the lift distribution of both aircraft has been optimized and for which they are trimmed, curves are then obtained by changing the angle of attack of the aircraft from this point

All of the above was achieved without using reflexed camber lines on the profiles of the Flying V. For the heavily swept middle wing section the profiles of the Flying V are almost symmetrical, for the outer wings they have a slight positive camber.

The chosen profile in the middle wing section is displayed in the following picture (see FIGURE 12). It is almost symmetrical only with slight modifications that the cabin cross section sits well into the front section. On Blended Wing Body type of aircraft symmetrical sections with a maximum thickness position of 30% are used without the occurrence of a shock for $c_l$=0.23, a relative thickness of 16% and at Ma>0.8. [8]. The maximum thickness position of 30% is adopted here.

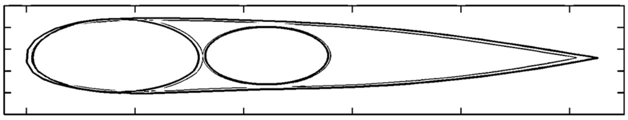

FIGURE 12. Proposed profile in streamwise direction with elliptical cuts for cabin and cargo section, almost symmetrical profile with an upper surface of a transonic profile and a slight middle loading

Turned 63° the profile can be displayed with the cabin and cargo cross section (FIGURE 13).

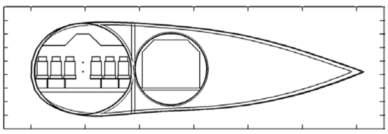

FIGURE 13. Cabin sketch and proposed profile section orthogonal to the leading edge of the heavily swept middle wing

[1] Absolute values for L/D are Airbus confidential

## 6.2. Mass

For a first mass estimation the Flying V was conservatively put together from scaled existing airplane parts. This way, a preliminary mass breakdown could be generated. The mass of the pressurized structure and outer wings was assessed as illustrated in FIGURE 14. For the pressurized sections A320 fuselage sections were scaled up. Additional mass was added because the Flying V cabin is not entirely circular. Its height to width ratio is 0.95.

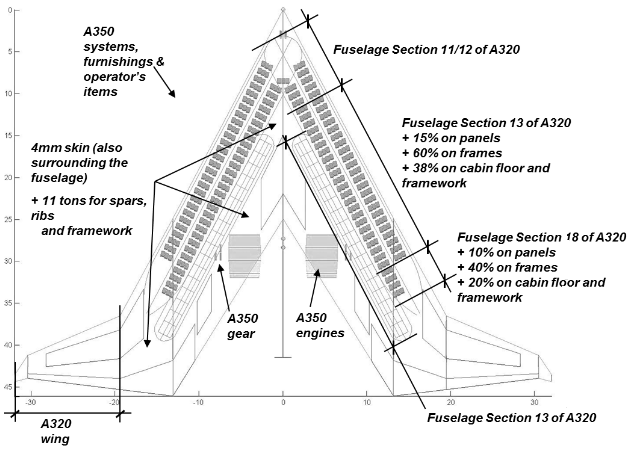


FIGURE 14. The mass of the pressurized structure of the Flying V was estimated by scaling existing aircraft components

The mass of the middle wing skin and the transition wing skin is estimated by assuming a skin thickness of 4mm. For the inner structure of the middle and transition wings a mass estimation was made with an iteration: The wing bending is calculated using the already assessed masses of the Flying V aircraft components and a first guess for its inner structure of the middle wing. Then, the wing bending is also determined for the reference aircraft. Then, for the requirement of no buckling, minimum rip distances and minimum rip thicknesses for the Flying V inner middle wing structure could be determined relative to the reference aircraft. Because the mass of the wing structure of the reference is known, a mass for the inner wing structure for the Flying V could then be calculated scaling the inner wing volume of the reference up to the Flying V but taking into account how rip distance and thickness would roughly change due to the no buckling requirement. The final spanwise mass distribution and lift distribution for the 1g and 2.5g case of the Flying V is shown in the FIGURE 15.

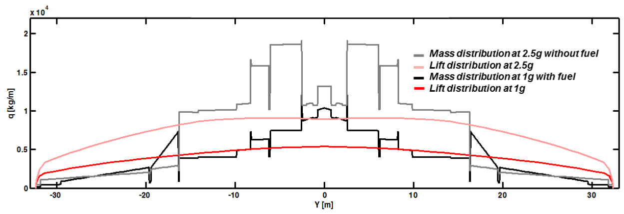


FIGURE 15. Spanwise distribution of mass and lift of the Flying V. Lower lines are for the 1g case, upper lines are for the 2.5g case.

As the Flying V has roughly the same capacity as the reference, the mass of systems and furnishings was adopted from the reference. Also the engine mass was kept the same.

In the end the MTOW for the Flying V was 2% lower than for the A350-900, so roughly the same.

## 6.3. Take-off and landing

The maximum angle of attack at take-off and landing follows from the chosen geometry and is roughly 12.5° (see FIGURE 16).

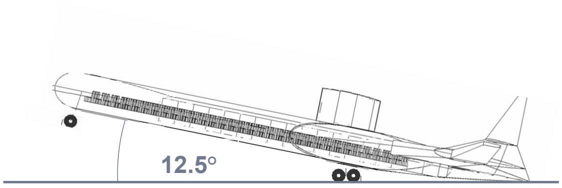


FIGURE 16. Maximum angle of attack for take-off and landing

Assuming the same speed for take-off like the reference aircraft, roughly 150kt at ISA+15, the lift coefficient at take-off is $C_L$=0.71.

The angle of attack needed to achieve this lift coefficient was calculated with ODILILA and is α=8.5°.

Maximum flap deflections for this case are 5°. (The control surfaces of the aircraft are shown in FIGURE 5.)

When the center of gravity is moved forward 5% MAC from its design position the required angle of attack at take-off changes to α=10.1° and the maximum flap deflection for this case is 10°.

## 6.4. Handling qualities

To display the maximum center of gravity range a load and balance diagram was drawn (see FIGURE 17).

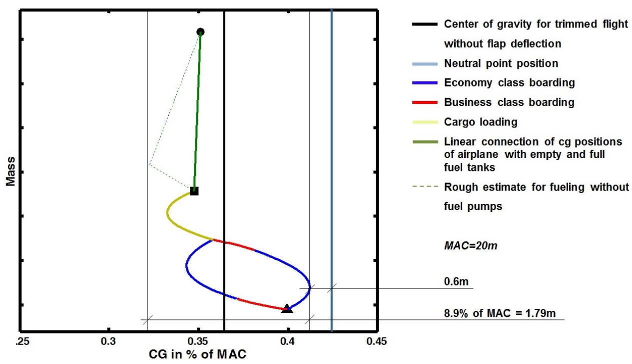


FIGURE 17. Center of gravity diagram[2]

[2] Absolute values for the mass are Airbus confidential

CG positions are displayed in percent of MAC. The CG position at OWE is displayed with (▲).
The CG position for which the aircraft is trimmed with no flap deflection at cruise flight is shown with the bold black vertical line.
The neutral point position is displayed with the bold blue vertical line.
Passenger boarding is displayed in from the front and from the back. The business class (red line) is placed in the front of the cabin sections. Cargo is loaded in the aircraft from the back. The MZFW is displayed with (■).
For filling the fuel tanks the center of gravity position of full and empty fuel tanks are connected with a straight line as a rough estimate. The MTOW is displayed with (●).

When no fuel pumps are used the center wing tank is filled up to roughly a half before the transition and outer wing tanks are being filled. This is estimated with the dashed line the outmost point being the center of gravity when the center fuel tank is filled to a half.

No substantial analysis of the lateral handling qualities is made in the scope of this work. It is, however, desirable to find out if the design is directionally stable at all.

A simulation shows (see FIGURE 18, FIGURE 19, and FIGURE 20) that the design can be made directionally stable with sufficient dihedral of the outer wings and winglets of a sufficient size. Aerodynamic derivatives for the simulation have been obtained with ODILILA.

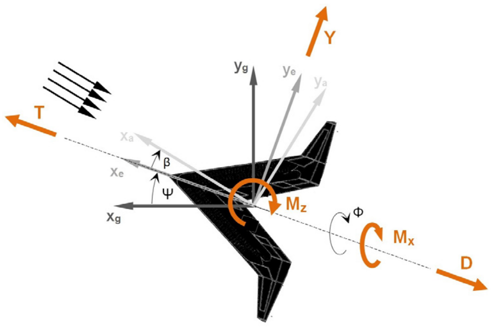


FIGURE 18. Model for the lateral handling quality simulation, T is the thrust, D is the drag, Y is the side force, $M_x$ is the moment around the longitudinal axis, $M_z$ is the moment around the vertical axis, Ψ is the azimuth angle, Φ is the bank angle and β is the sideslip angle

According to the simulation model, a Flying V design with the chosen geometry and with no dihedral of the transition and outer wings and no winglets is instable.

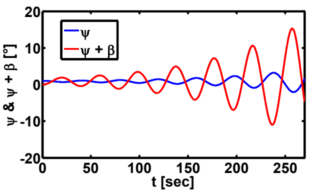


FIGURE 19. Flying V with no dihedral of transition and outer wings, disturbance: β=-1°, cruise flight

For 6° dihedral on transition and outer wings, and winglets with a total projected lateral area of 16m$^2$ the design is stable according to the simulation model.

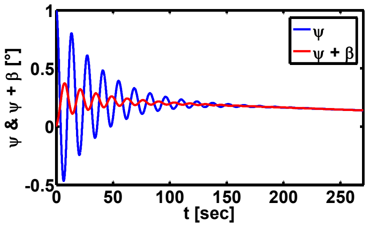


FIGURE 20. Flying V with 6° dihedral on transition and outer wings, and winglets with a total projected lateral area of 16m$^2$

## 7. RADIO CONTROLLED MODEL OF THE FLYING V

For demonstration purposes and as validation for some of the results obtained with ODILILA a radio controlled aircraft modell of the Flying V was built.

The parts for the wings were cut out of styrofoam (see FIGURE 21 and FIGURE 22).

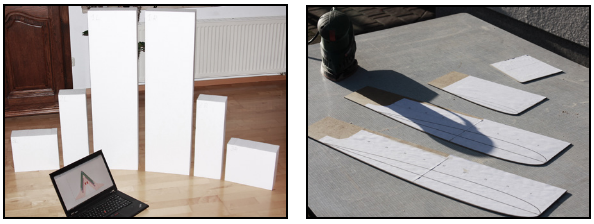

FIGURE 21. Blocks for the wing elements were cut with a hot wire cutter and the profiles were cut out of wood

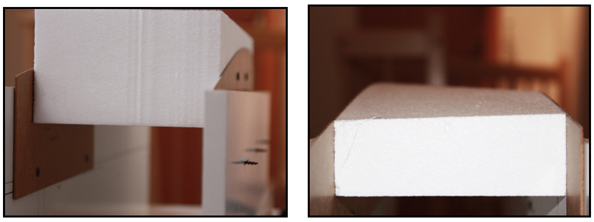

FIGURE 22. The profiles were arranged at the calculated position with the calculated twist and the wing shape was made with the hot wire cutter as an even ruled surface

Then the parts were arranged as the Flying V (see FIGURE 23).

FIGURE 23. The wings were glued together with styrofoam glue and smoothed with sand paper. The flaps were cut out and the model was covered in a thin layer of glass fiber.

The model was equipped and tested in preparation for its first glider flight (see FIGURE 24 and ).

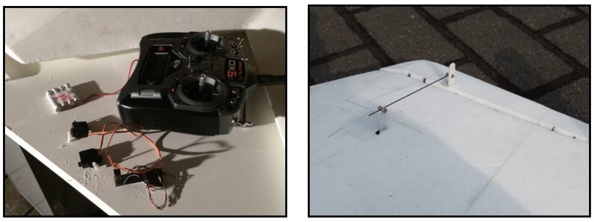

FIGURE 24. Two servos were installed to actuate the flaps. The battery was installed in the front to place the center of gravity to the calculated position

FIGURE 25. The glider model weighs 770g and has a wing area of $0.43m^2$. To achieve the design $C_L$=0.25 a speed of roughly 40km/h is required. After first slower tests with running the model was brought up to 40km/h with a car. The rudders were tested and the model seemed well trimmed for a neutral flap position at this speed and stable.

The first glider flight was made after throwing the model airplane from a hill (see FIGURE 26).

FIGURE 26. First flight of the Flying V (28.02.2014, Berlin, Germany): The model was thrown from a little hill out of a height of roughly 3.5m. After a short and fast decent to gain speed after the throw a straight glide path could be taken up on which the Flying V flew roughly 90m. The airplane was easy to control and landed smoothly.

As next steps engines were installed on the model (see FIGURE 27) to demonstrate longer flights with more sophisticated maneuvers.

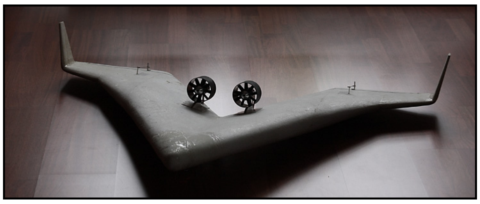

FIGURE 27. With the engines and batteries the weight of the model was increased to 1400g. The required speed for the design $C_L$ is then 50km/h. As engines electro impellers were taken. The batteries were installed in the underbelly.

The test pilot was an experienced pilot for model airplanes and reported that the Flying V model was easy to fly.

FIGURE 28. Powered version of the RC model of the Flying V taking off for the first time (13.04.2014, Hamburg Finkenwerder, Germany)

FIGURE 29. RC model of the Flying V making a sharp turn.

The test pilot could fly sharp turns without difficulties. Also a role was possible. A stall test was also performed. After the angle of attack was increased further and further and the speed was reduced the nose of the Flying V fell suddenly back down again and the model recovered.

The landing was smooth.

FIGURE 30. RC model of the Flying V on final approach for landing

## 8. CONCLUSION

Preliminary estimations made in this work indicate that the Flying V aircraft configuration might have a benefit over the reference in terms of aerodynamics (10% higher L/D) and mass (2% lower empty weight). As reference aircraft the A350-900 was chosen which has roughly the same capacity as the Flying V and the same wing span (see FIGURE 31).

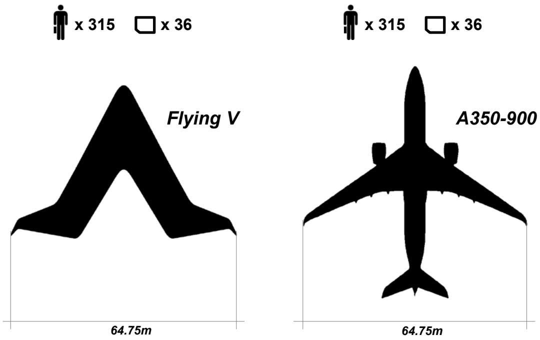


FIGURE 31. Comparison of Flying V and reference

More qualitative arguments in favor of the Flying V which could be derived are the compactness and simplicity of the configuration (less parts, no high-lift devices, no fairings, straight lines) and the shielding of the engines from the ground (low noise). Remarkable is also the elliptical lift distribution of the naturally stable design using only a moderate wing twist and no reflexed camber lines. A radio controlled model of the Flying V was presented in this work to demonstrate these aerodynamic characteristics and support the estimations and simulations which were made. Some recommendations for future work on the concept are:

- Design of a structure necessary to assess the mass more detailed
- More detailed aerodynamics calculations necessary (wave drag estimation, 3D effects, low speed – $C_{L,max}$)
- Take-off and landing calculation necessary (points of interest: take-off rotation, bank angles, engine failure, cross wind landing)
- Critical cases for emergency evacuation have to be found and investigated
- Chosen configuration is not fixed, position of cargo compartments, fuel tanks, engine integration and planform geometry have to be studied further
- General size and capacity of Flying V type of aircraft will be important for further studies (family concept)

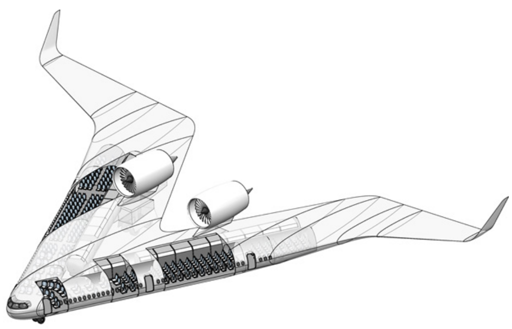

FIGURE 32. CAD model of the Flying V configuration

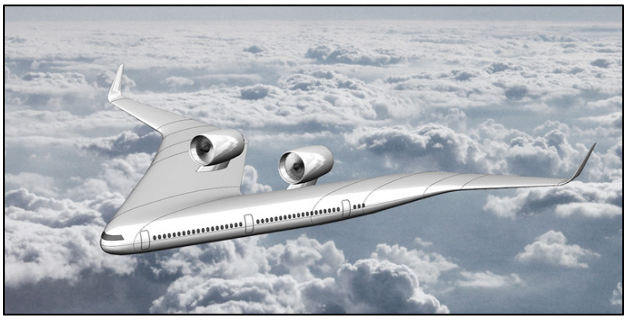

FIGURE 33. Artistic impression of the Flying V

So far, the Flying V is an idea. Everything which was presented in this work can be regarded as the first step of a long iteration which will be necessary to develop the concept further.

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