A Study on Flight Mechanics of Tailless Aircraft

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1 Introduction

Flying Wings or Tailless aircraft are fixed-wing aircraft defined by their lack of a definite or pronounced fuselage and absolute absence empennage. Jack Northrop defined these aircraft as *'A type of airplane in which all of the functions of a satisfactory flying machine are disposed and accommodated within the outline of the airfoil itself'*. These aircraft are designed specifically to make best use of the aerodynamics effects of the wing design in order to reduce induced drag due to inclusion of empennage in the airframe and tail section vortices. A typical Flying Wing/Tailless Aircraft is shown in Fig.1.

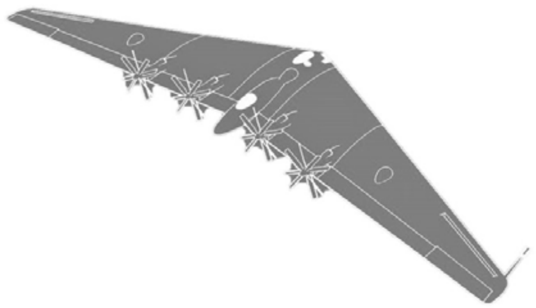

Fig. 1 Flying Wing design mockup. Courtesy: Sridhar Kota, Illustration: John MacNeill, IEEE Spectrum

The military application of building flying wings initially began as a method to minimise radar signature by reducing the Radar Cross Section (RCS), done by eliminating the tail section. This configuration gave rise to development in better stealth technology to drop payloads behind enemy lines undetected. The civilian applications include utilising the low induced drag to the advantage of increasing fuel efficiency for passenger aircraft. In this regard, Blended-Wing Bodies (BWB) have been seeing considerable progress towards replacing conventional aircraft.

2 History

Flying Wings or Tailless aircraft have been a topic of study since the early days of aviation. The earliest known work on flying wings was done by Hugo Junkers in 1910 on his biplane. In his patent No.253 788, he famously said *"The wings should provide space for not only their engines and fuel, but also for payload and crew"*, but he was limited by the technology of his time to realise this. Early developments in building flying wings were successful only in the 1940s when the Horten Brothers of Germany won the tender to build advanced flying wing concepts, the *Horten Ho series* (Fig.2) to aid in the war efforts for the German Third Reich. [1]

Fig. 2 The Horten Ho 2, 3 and 4 Gliders. Courtesy: Nickel and Wohlfahrt [2]

After the war under 'Operation Paperclip', Jack Northrop got his hands on a few of these concept aircraft and developed them further with some of his own findings and consequently came up with the YB-49 Flying Wing in the late 1940s, the predecessor to the infamous B-2 Spirit which was developed later in 1989.

3 Aerodynamic Control and Stability

Flying Wings, just like conventional aircraft work on the balance of the four forces on the wing. As we know, lift is created by a combination of both Bernoulli's Principle and Newton's Third Law of motion. Much like conventional aircraft, flying wings use control surfaces distributed across the wind span for direction control. In modern tailless aircraft, it has become easier with technology development related to on-board flight controllers which work better and are more reliable than compared to manual flight. Examples of these unmanned flight systems are found in the Lockheed F-117 Nighthawk, Northrop Grumman X-47B, Boeing X-45C and others [3, 4, 5]

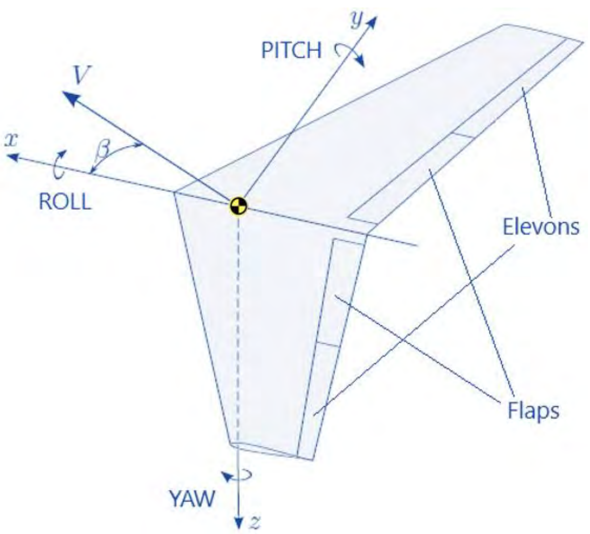

Fig. 3 Axes Notation and Sideslip angle β definition.

Fig.3 shows the pitch, roll and yaw notations in a flying wing along with the sideslip angle β. To control the pitch, inboard flaps on both sides of the wing are deflected together like a typical elevator. For yaw control, the flaps on either the left or right are deflected up and down to create drag on that wing in that direction, thereby turning the aircraft. Roll control is achieved by deflecting the flaps on both wings in opposite directions, just like a conventional aircraft.

3.1 Pitch Stability

Consider a cross section of the wing of a conventional aircraft as shown in Fig.4. In the first image, at a low Angle of Attack (AoA) the pressure distribution is as shown, where the Centre of Pressure (C_p) is towards the aft. At higher positive AoA, the C_p shifts towards the leading edge. Conversely, at a negative AoA the C_p shifts further towards the trailing edge. This shift causes negative instability where the wing (aircraft) tends to flip at the slightest deviation from the perfect AoA which is accentuated by the chord length of the airfoil.

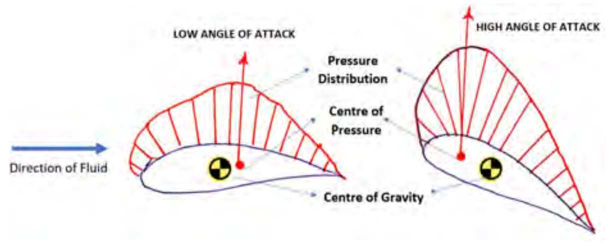

Fig. 4 Pressure distribution and shift of C_p along the airfoil with increase in AoA.

For this reason, conventional wings have tails to counter and control this instability with a positive difference in the elevator called *decalage*. But in flying wings, due to the absence of elevators, the airfoil itself is given a positive *reflex* at the trailing section to compensate for this decalage. This produces the corrective force that tends to bring the aircraft back to level whenever there is a pitch up or pitch down. It is for this very reason that flying wings have a forward Centre of Gravity (CG) ahead of the C_p much like a dart, but controlled by the reflex.

Although reflex seems to be a wonderful solution, it has its drawbacks. For one, it is not as efficient as a conventional wing due to low C_{Lmax} requiring higher AoA at takeoff and also because it loses some of the Newtonian lift produced in order to stabilize the wing.

3.2 Roll and Yaw Stability

The Control Surfaces of flying wings are designed to compensate for the stability provided by a tail. Yaw stability is achieved by a method called *differential drag*, where the drag on one side of the wing is increased more than on the other side causing a directional change of the aircraft in that direction.This is achieved by one of the following methods:

- Spoilers: A spoiler surface is raised on the topside of the wing which functions as airbrakes creating drag in that direction.
- Split-type Ailerons/Elevons: The Ailerons/elevons on the trailing section are designed to split into two surfaces on the top and bottom opening to the aft of the aircraft. By actuating them differentially, more drag is create on one side, causing a directional change.

- Spoilerons: This is nothing but creating a higher deflection of the ailerons/elevons on the top side of the wing to function as both aileron and spoiler.

It can be seen that flying wings have are designed with a sweep. In most cases, wings are swept in order to achieve higher speeds and reduce the onset of pressure drag over the leading edge. But in the case of flying wings, this has more to do with stability. With the sweep, the CG is shifted forward and due of the absence of the tail, it needs a longer moment arm to stabilize the flight. Here, the sweep increases the length of the moment arm thereby helping restore the aircraft to equilibrium. [6]

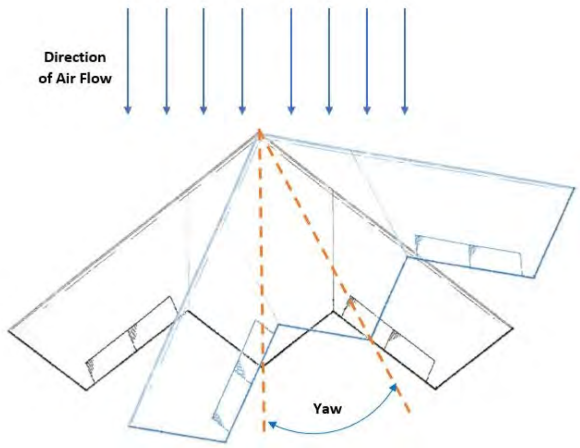

Fig. 5 Yaw and Roll self correction for stability

When the aircraft performs a yaw as shown in Fig.5 at an angle to the direction of incoming air, we see that the starboard side of the flying wing has more projected area compared to the portside. This generates more lift on the right of the wing. This lift causes an induced roll motion. Thus, in a flying wing, there exists a yaw-roll couple, and also a corrective yaw motion to bring it back to equilibrium. So every time the aircraft performs a yaw, a corresponding roll in that direction also persists, which is used to the advantage of banking the flying wing [7, 6]
The downside of this is that the aircraft is constantly unstable at turning and banking due to the continuous cyclic correction producing a wobble that tries to stabilise the aircraft normal to the flight direction.
This wobble effect can cause instability and is avoided by trying to correct the airflow over the wing to flow normal to the axis of the aircraft again. The way to do this is by introducing *Wing Fences* [8] on the surface of the wing as shown in Fig.6.
Using wing fences over the surface of the wing prevents spanwise airflow and redirects airflow longitudinally. This produces a corrective yaw force that prevents the wobble effect.

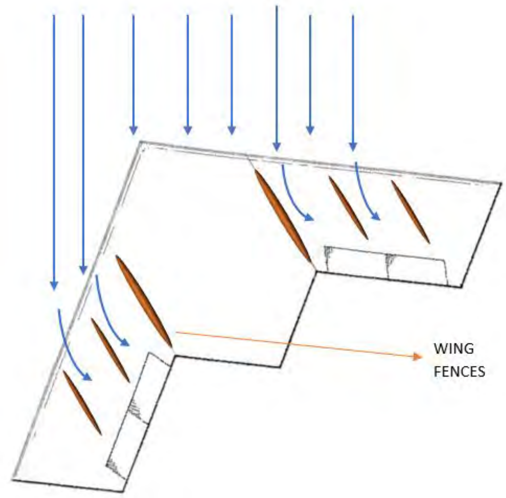

Fig. 6 Using Wing Fences to redirect airflow

4 Future Outlook

Flying Wings are continuously being developed for future applications pertaining to military, passenger aviation and also for logistics. Due to the high instability of these aircraft, a flight computer/autopilot is usually the one doing the flying. NASA has been working on the X-56 platform to study the flight characteristics of flying wings as a way to counter the adverse yaw and directional instability [9]. NASA has also greenlit and funded the 'Silent and Efficient Supersonic Bi-Directional Flying Wing' [10]. Many commercial aircraft corporations are also looking into flying wing concepts for passenger aircraft, which looks to be the future of aviation. It can thus be presumed, the future for Flying Wings/Tailless aircraft is shaping up to be bright and is gaining momentum in academic and industrial fields to become a viable option for the future of aviation.

Fig. 7 NASA X-56 test platform and Bi-directional flying wing concept

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