



Continuing Development of a Novel Certifiable Airliner “Gondola” Using Liquid Hydrogen

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Abstract

With growing realization of environmental issues, our vision of Aircraft development to 2050 is changing. To eliminate the reliance on fossil fuels, there is focus on using liquid hydrogen (LH2) in civil aviation. Previously, to keep the LH2 away from payload (crew and passengers), we developed along the lines of an asymmetric twin-body layout “Gondola”. This paper continues developing the understanding of Stability and Control (S & C) by proposing emulating and extending the well-known flying Model 202 asymmetric configuration pioneered by Rutan. Several CFD results are presented.

Keywords: Aircraft Design and Integrated Systems, Aerodynamics, Flight Dynamics & Control

1. Introduction

With growing realization of environmental issues, our vision of Aircraft development to 2050 is imagined as shown in **Figure 1**, [1] and [2].

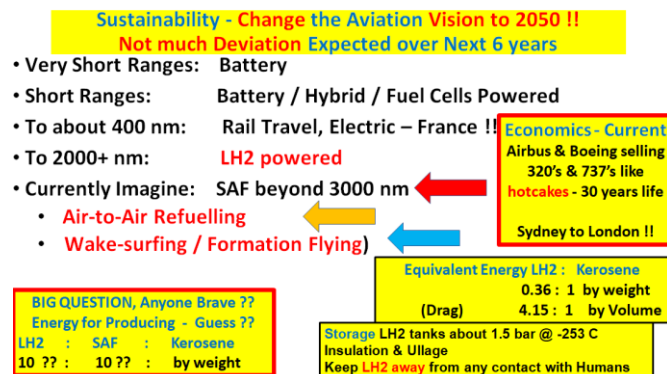


Figure.1 Sustainability - Change the Aviation Vision to 2050

To eliminate the reliance on fossil fuels, there is enhanced focus on using liquid hydrogen (LH2) in civil aviation. LH2 being (a) cryogenic with low energy density per unit volume and (b) potentially explosive, presents a big challenge to designers in arriving at a safe and certifiable aircraft [2]. Innovation is called for. Low energy density and heavy cryogenic tanks incur performance penalties compared with kerosene or SAF powered aircraft. Overall, the flight experience with LH2 is very limited and knowledge gaps exist in its physical implementation in airframe and propulsion systems.

At the 33rd ICAS 2022 Congress, we introduced “Gondola” [1], a novel certifiable medium range airliner using LH2, **Figure 2**, The fuel system is isolated from the passenger accommodation to avoid the risk of fuel explosion and cryogenic fuel spillage in the event of a crash landing. A twin fuselage layout with fuel in one fuselage and passengers in the other with a dry wing satisfies this requirement. The differing fuel and passenger volumes led to asymmetry. This twin-body concept has generated much interest. In preliminary estimates, **Figure 3**, compared with a conventional airliner, the twin’s weight is higher

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but with a higher aspect ratio wing and lower wing bending moments, efficiency can be regained for the twin. Note the fuel weight percentage for LH2 is 3 times less than for the conventional medium range airliner.

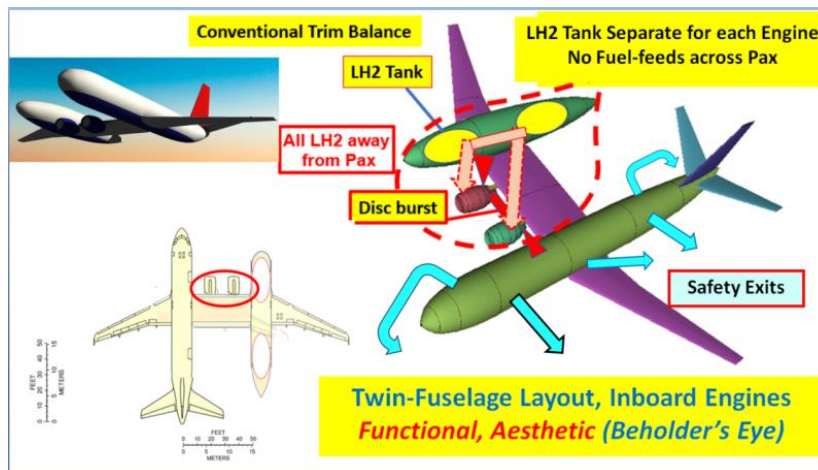


Figure 2 “Gondola” Aircraft & features

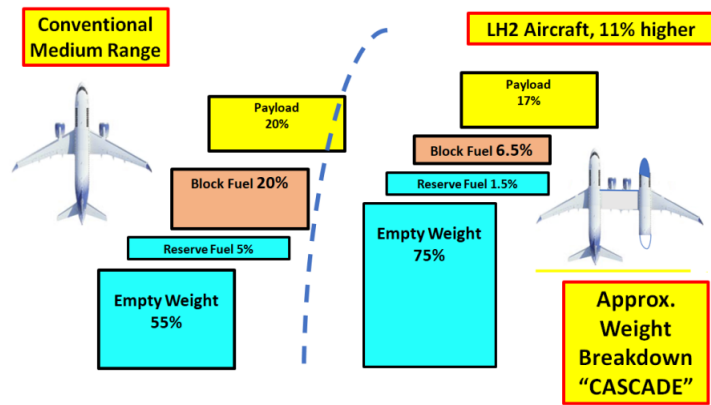


Figure 3 Comparing Weight Breakdown cascade: Conventional & Twin

With further interpretation / understanding of certification issues, it has become clearer / more transparent that there is a need for much experimental evidence [2]. This must be catered for to ensure future success. We are concerned here in continuing development of the concept and in particular focus is on understanding the implications of asymmetry.

2. Stability & Control (S & C) and Trim

For S & C analyses, six-degree of freedom equations need to be solved. For a symmetric aircraft, we can simplify these into two independent sets for longitudinal and lateral motion. The longitudinal set deals with short period oscillation and phugoid mode. Dutch roll, spiral stability and damping in roll are dealt in the lateral set.

In asymmetric aircraft, cross-couplings occur which can produce both longitudinal and lateral motion from a single movement of a cockpit control. A fly-by-wire system is needed, engaging all aerodynamic control surface and propulsion, **Figure 4**. The system translates the pilot demand into the desired flight response. The limiting feature of such a control system is the aerodynamic effectiveness of the control surfaces and propulsion integration. An iterative solution between the longitudinal and lateral sets appears as the easiest way to make it all tractable.

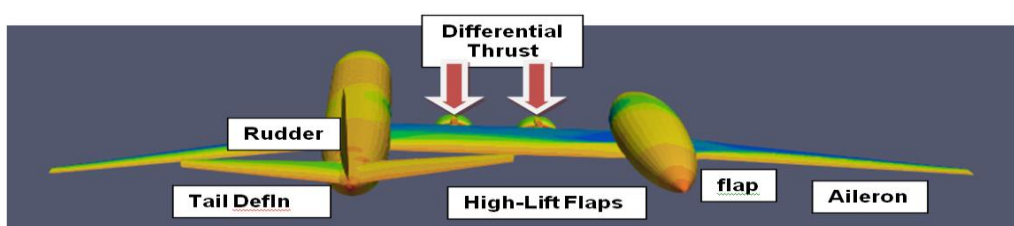


Figure 4 Controlling Means for an Asymmetric Aircraft

An associated problem is the ability to trim the aircraft for 1G flight on all three axes. If the lateral position of the centre of lift does not coincide with the lateral CG, then a trimming control surface (e.g. aileron) is necessary. A complication is that the span-wise distribution of lift determines the lift-dependent drag and so a degree of optimisation is required to improve efficiency.

A similar problem is trimming the engine thrust so that resultant thrust line balances the line of action of the drag (which may be offset from the aircraft centre-line). Possible solutions are to have differential thrust capability or (preferably) using rudder & aileron deflections as lateral trim surfaces.

3. Flight & Field Operations

In the course of a normal flight, fuel would be burnt off from the right-hand fuselage and the lateral CG will migrate towards the left hand side of the centre-line. This will increase the average end load on the left-hand main landing gear. The effect on tyre wear and landing gear maintenance requires further detailed analysis. Further, the fuel weight being low, the landing weight is 90-95% of MTOW, so this implies good high lift system. However, the low inner sweep wing makes that easier.

Selected results are presented here to give a flavour.

We begin with assessing chordwise C_p and spanwise loadings on a typical configuration at high speeds, **Fig.5**. These look reasonable.

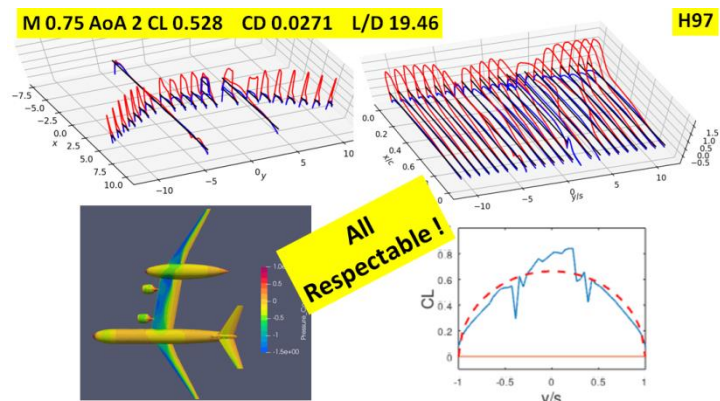


Figure 5 Typical configuration chordwise C_p and Spanwise lift loadings

In **Figure 6**, we look at effects of Tailplane deflection at high speed.

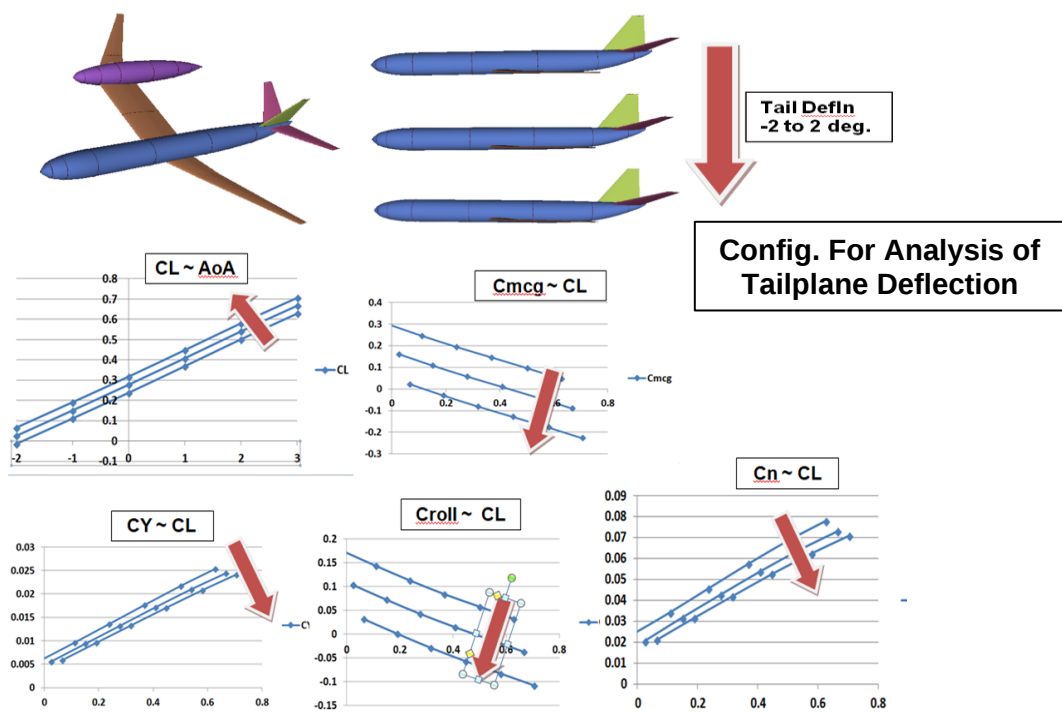


Figure 6 Effect of Tailplane Deflection on Longitudinal and Lateral Forces and Moments

4. Sideslip Effects on a configuration with Fin off-set 2°

The component breakdown is shown in **Figure 7**. The Fin contribution is large for CY and Cyaw but not for Croll.

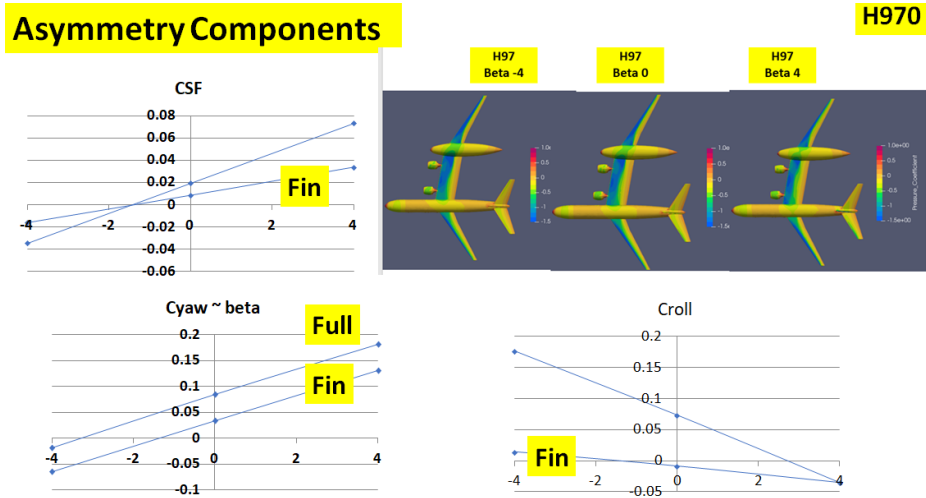


Figure 7 Variation of asymmetric Forces & Moments with sideslip

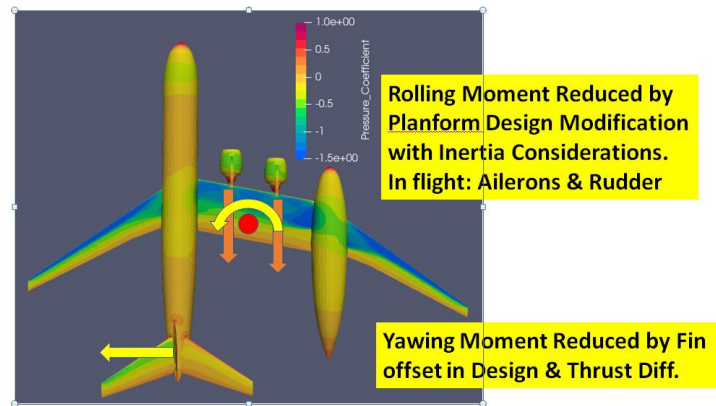


Figure 8. Controls Available for Asymmetric Aircraft

Figure 8 summarizes the option for controlling an asymmetric aircraft and we have lots more to do!

5. Dry Wing and Innovation Options

The “dry” high aspect ratio wing offers several options for incorporating modern developments in wing technology e.g. aeroelastic tailoring, flared folding wing tips (Bristol University & Airbus [3]). One idea, **Figure 9**, could be to use forward swept outer wing panels. This could allow a well-designed inner wing panel to “absorb” the main undercarriage as well as offering substantial lift. Asymmetric Aeroelasticity aspects are involved. Such an arrangement also obviates tip stall and encourages reasonably high CL max (Landing weight is no more than 7-10% lower than the take-off weight. A specimen CFD simulations is shown. Further studies including optimisation and balance of the wing planform are in progress.

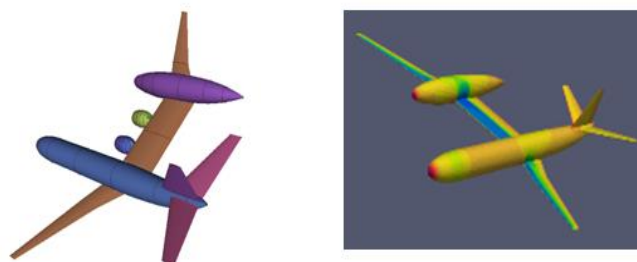


Figure 9 Advanced Considerations with FSW – First Attempt, Undercarriage Placement, Advantages: No Tip stall, Reduced outer BM.

Overall, we infer that theoretical work so far does not suggest any major showstoppers that modern technology can't resolve. However, it will be useful to gain some practical experience (and recognition / acceptance). Let us look at some unusual radical aircraft that have flown, **Figure10**, many with asymmetry. A topical (obvious) question arises: Can we reduce the asymmetric behaviour of such an aircraft with two unequal fuselages by redesigning the wing planform?

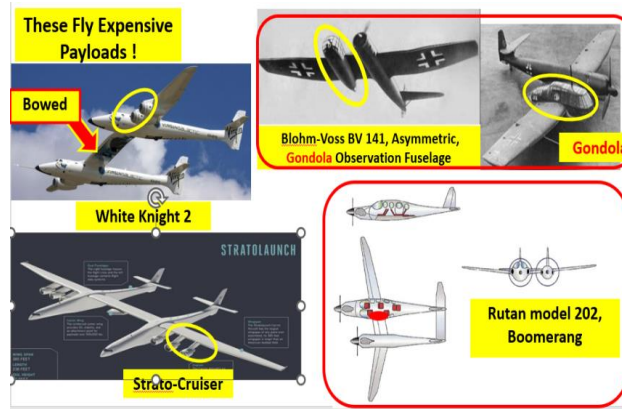


Figure 10 Unusual, Radical Configurations

An idea in this context is to consider the Rutan model 202 Boomerang [1, 4]. A practical way forward is then to begin with low-speed consideration of such an aircraft and extend the understanding with CFD studies and possibly build a reasonable fidelity low-speed research UAV (either a Wind Tunnel programme or indeed a radio-controlled flight model). That may lead to an Experimental X-plane!

6. Notes on Model 202

The model 202 was based on the fuselage and cabin derived from the popular Beechcraft twin Baron (wing aspect ratio AR 8.5). The model 202 minimized the propulsion asymmetry effects that arose with one engine in-operative on the Baron. A moderate Forward Swept wing (FSW) of higher aspect ratio (13.2) on the 202 allowed the CG relationships to be like those of the Baron. Higher efficiency pf? 202 was due to AR increase, The FSW gave a very significant advantage in reducing the wing-tip stall tendencies.

Some configuration particulars are briefly:

Wing span 36.7 ft

MTOW 4242 lb, 1922 kg, Max speed 283 kt, Stall speed 88 kt (at 96% MTOW)

Ratios: OEWR 0.56, Max. WPR 0.235, Max. WFR 0.24

Cruise CL 0.35 to 0.5

Figure 11 shows how the simplified CFD model has been deduced from the model 202. With 6 basic interchangeable components, we can organize various layouts for fuselage separation analyses.

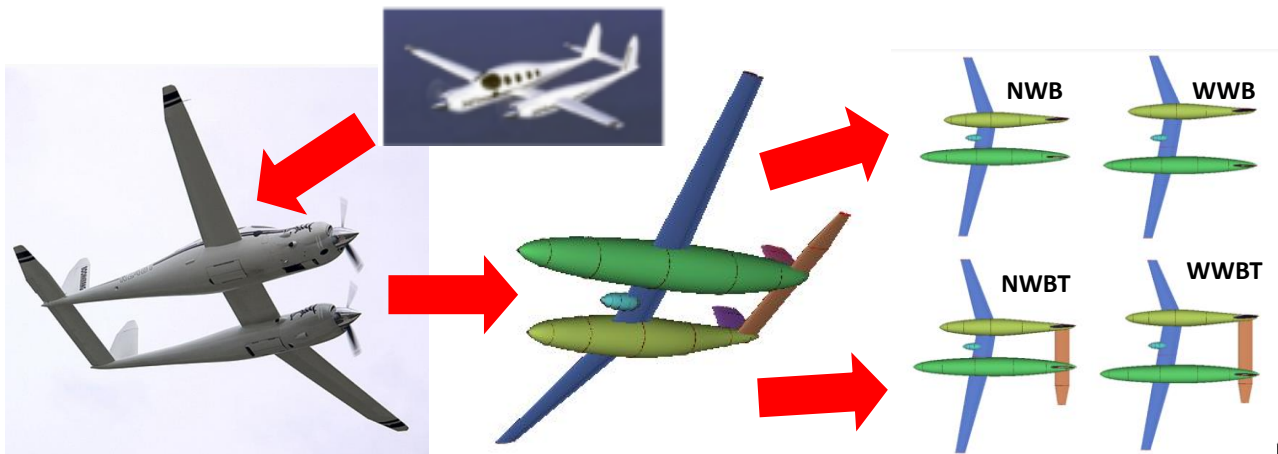


Figure 11 Deducing Research Model Configurations: NWB, NWBT, WWB & WWBT

7. Modelling & Results

7.1 Geometry used in modelling with SU2 CFD Solver in Euler mode

Span 20 units, Area S 32.8, Wing Aerofoil SC(2)-0412, Tailplane Aerofoil NACA 0008

CG reference Locations: 0.735 unit for NWBT, 0.984 unit for the WWBT (slightly longer Tail span).

We look at several, longitudinal, directional, and lateral aerodynamic properties from S & C viewpoint.

7.2 Effect of Bodies Spacing, NWBT & WWBT

Longitudinal properties of the two configurations are compared in **Figure12**. The major difference is due to the neutral point being slightly more forward for the configuration with narrow spacing (NWBT).

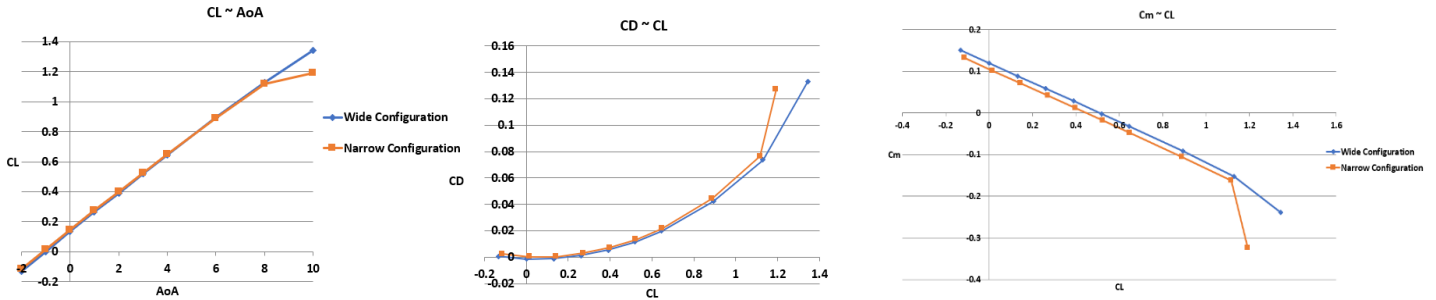


Figure 12 Effect of Bodies Spacing, Longitudinal Properties

For consideration of lateral and directional properties an important relationship, dynamic Yawing derivative due to sideslip, defined in terms of AoA α and AoS β is:

$$C_{n\beta_{dyn}} = C_{n\beta} \cos \alpha - \left(\frac{I_z}{I_x} \right) C_{l\beta} \sin \alpha$$

For stability $C_{n\beta_{dyn}} > 0$

This is particularly important as AoA increases and positive derivative $C_{l\beta}$ comes into action, decreasing the dynamic stability level.

As the body spacing increases, the inertias I_z and I_x both increase.

7.3 Effect of Sideslip, AoA 3°, NWBT & WWBT (Body Spacing alters)

Figure 13 shows the effects on various forces and moments.

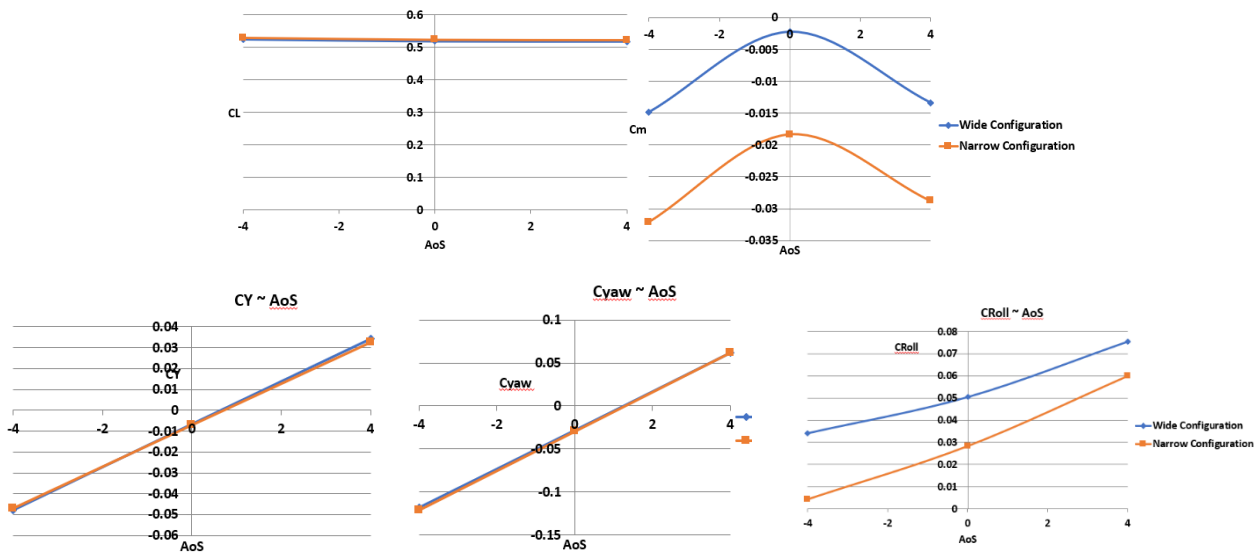


Figure 13 Effect of Sideslip, AoA 3, NWBT & WWBT

We note that for CY and Cyaw, there is no perceptible effect due to spacing. All show positive slopes with respect to β . The rolling moment derivative with respect to sideslip is some 20% less - a step in

right direction for from viewpoint of dynamic parameter.

7.4 Component Breakdown, NWBT & WWBT

Figure14 shows the component forces and moments breakdown for the narrow configuration. As anticipated, the bodies add positive C_m to the wing only case which is then trimmed by the tail. The tail is in the downwash of the main wing and introduces some extra lift as well as shifting the neutral point aft. The aircraft balances at CL about 0.43.

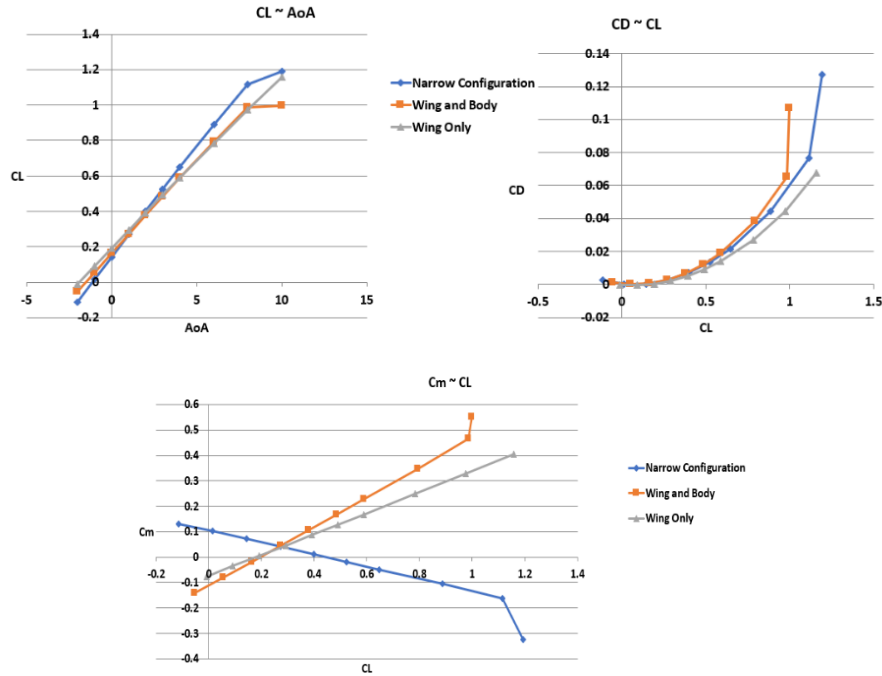


Figure 14 Component Breakdown, NWBT

Figure15 shows the component forces and moments breakdown for the wide configuration. As for the previous case, the bodies add positive C_m to the wing only case which is then trimmed by the tail. The aircraft balances at CL about 0.5.

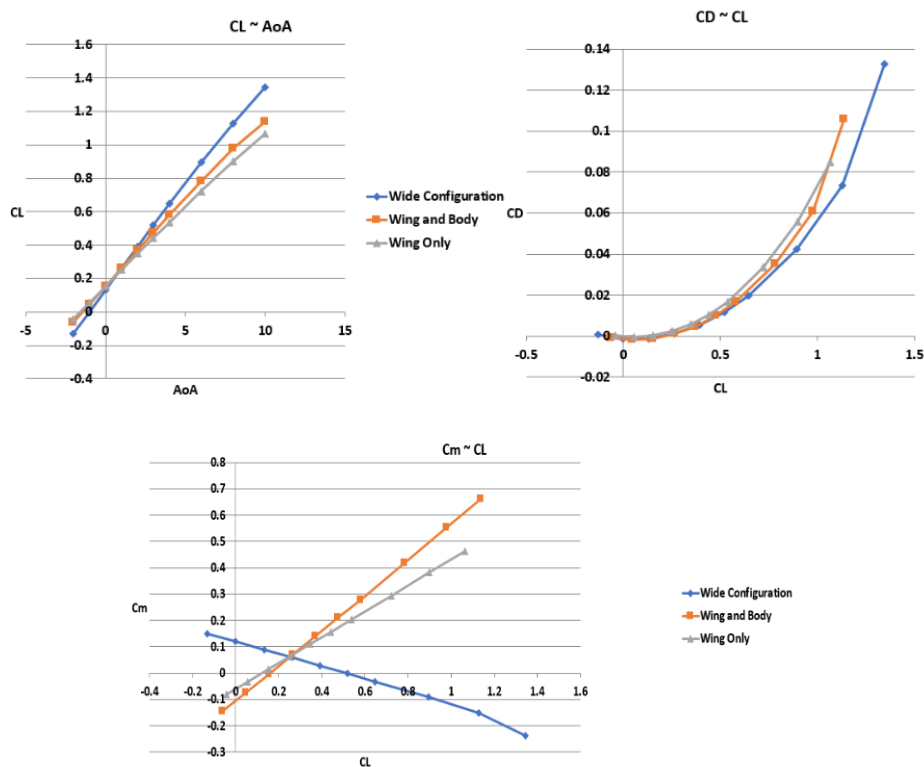


Figure 15 Component Breakdown, WWBT

7.5 Spanwise Loadings

Five cases are considered, Wing alone, NWB, NWBT, WWB and WWBT.

Figure 16 shows the spanwise loadings and upper surface C_p distributions on the wing alone case. Near elliptical loading (red dotted line) has been obtained.

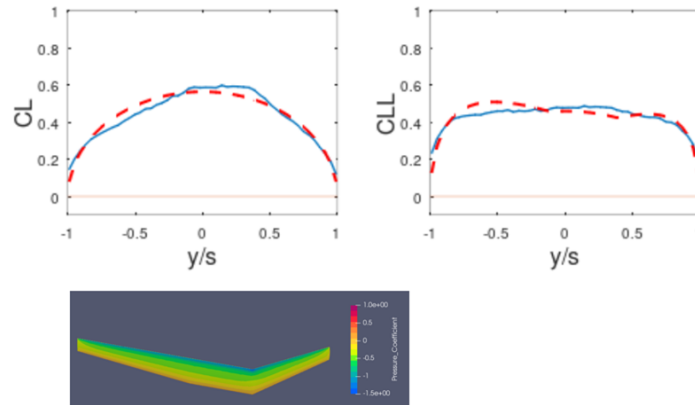


Figure16 Wing only, Spanwise Lift Loadings and C_p Distributions on Upper Surface

Figure 17 refers to configurations NWB & NWBT. It shows the spanwise lift loadings and C_p Distributions on upper surfaces. Note the (concertina type) discontinuities that appear because of CFD cuts with local chord accounted for, through the bodies. In a similar vein, **Figure 18** refers to configurations WWB & WWBT.

Having gone through step-by-step studies mentioned in this paper, we have added to the confidence in proposing that asymmetric twin body aircraft are feasible for practical experimentation. This includes the configurations with widely separated bodies as required in the LH2 “Gondola” concept.

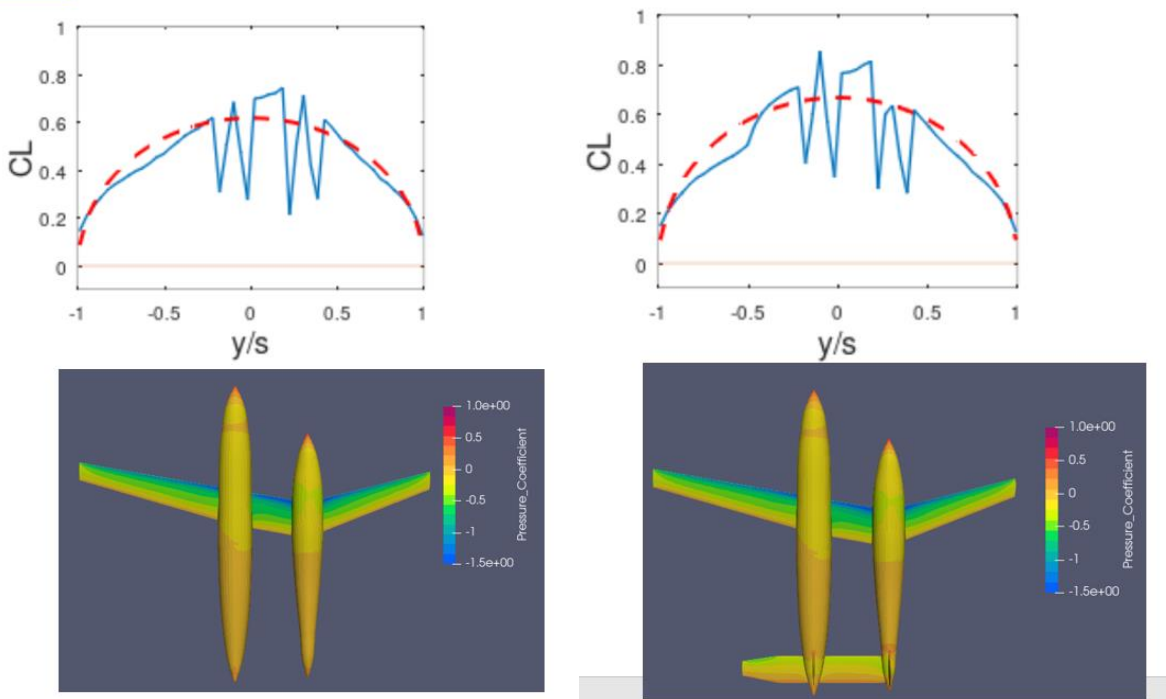


Figure 17 Configurations NWB & NWBT, Spanwise Lift Loadings and C_p Distributions on Upper Surfaces

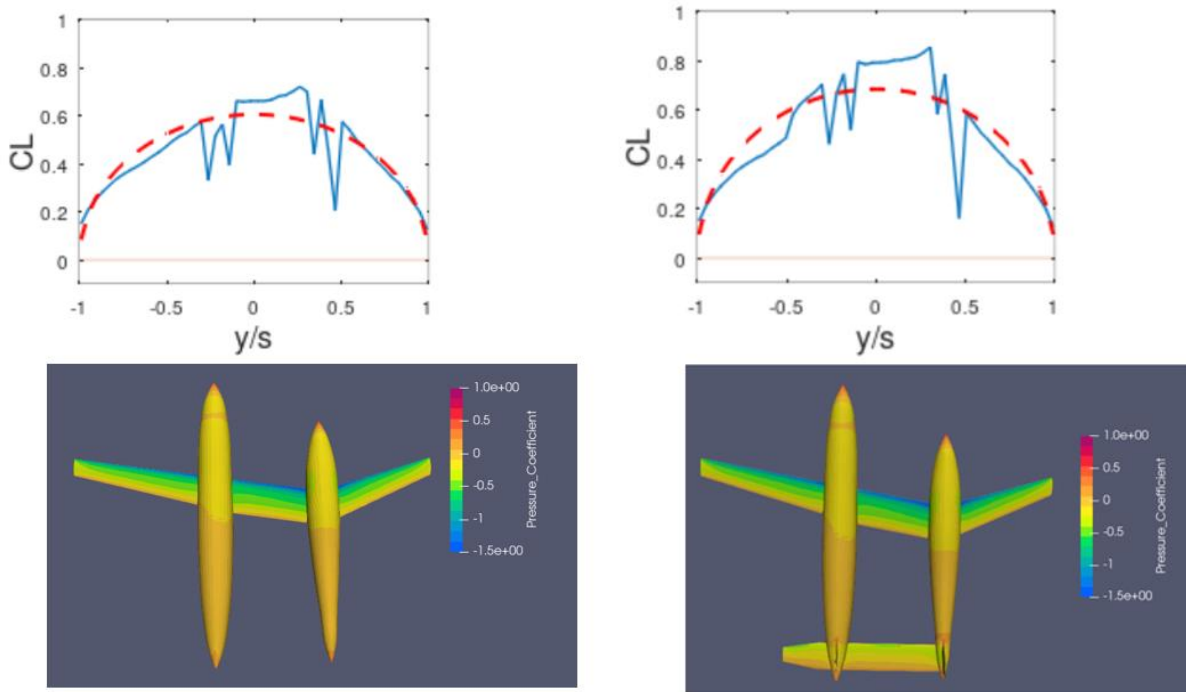


Figure 18 Configurations WWB & WWBT Spanwise Lift Loadings and Cp Distributions on Upper Surfaces

8. Conclusions

In previous work, we introduced the novel certifiable LH2 medium range airliner “Gondola” concept. To keep the LH2 away from payload (crew and passengers), we developed along the lines of an asymmetric twin-body layout.

To reduce the complexities of asymmetric handling qualities, an idea is to “tailor” the wing planform parameters. This brought into consideration the twin-fuselage concept used in the Rutan model 202 Boomerang. An additional feature was employing moderate forward sweep that prevented / delayed wing tip stall.

To continue advancing the understanding, of such concepts, we proposed gaining experience on asymmetric layouts derived from the model 202, using CFD and then build a flying model.

Several CFD predictions are presented to show the effect of geometry variations, particularly body spacing.

We have added to the confidence in proposing that asymmetric twin body aircraft are feasible for practical experimentation, leading toward the “Gondola” concept.

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