33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS
2022
SWEDEN

DESIGN OF AN ADVANCED EMPENNAGE AND REAR FUSELAGE CONCEPT FOR A COMMERCIAL AIRCRAFT

Raul C. Llamas Sandín, Caleb D. Handal Rivera

Future Projects Office, Airbus Operations SL, Getafe, Spain

Abstract

The Clean Sky 2 “Advanced Rear End” project (ARE) aims to significantly improve the efficiency of the empennage and the supporting rear fuselage of a mid-sized conventional commercial transport aircraft. The expected performance improvement at aircraft level stems mainly from two sources:

- Configuration benefits: including favorable aeroelastic behavior for stability, reduced size of the horizontal and vertical tail planes allowed by a reconfiguration of the component and smaller wetted area and weight of the rear fuselage.
- Improved applied technologies, including from a highly streamlined configuration design synthesis and analysis process to the application of anti-ice coatings and passive shapes which will allow to remove the need to consider the aerodynamic penalty imposed by ice accretion in the sizing of the tail planes.

At this stage of the project (approximately at 50% of completion) a robust rear-end concept has been produced which matches the target flight mechanics characteristics of the reference aircraft with an expected fuel burn saving due purely to configuration effects in the order of 0.7% at aircraft level.

Keywords: Aircraft Design, Forward Swept, Unconventional Configurations

1. Project Objectives and Concept Rationale

1.1 Concept rationale and basis for comparison

The reference configuration of the ARE project is a Forward Swept Horizontal Tail Plane (FSHTP) concept (Fig. 1), which seeks to exploit the following key performance drivers;

- Increased max. lift coefficient and control power due to FSHTP and 3D aerodynamic effects
- Increased stability characteristics (lift slope) for a given area from positive aeroelastic coupling due to the forward sweep of Horizontal Tail Plane (HTP) and increased aspect ratio
- Reduced leading edge sweep of the HTP, facilitating Natural Laminar Flow
- Reduced area of the rear fuselage, more compact configuration, Auxiliary Power Unit (APU) moved forward
- Reduced Vertical Tail Plane (VTP) size on the basis of an aft shift of its position

with the following Recurring Cost savings enablers:
- Reduced structural weight as a primary driver
- Reduced number of structural parts and length of systems routings
- Simplified assembly and maintenance processes enabled by the configuration

and the following Particular Configuration Risks:
- APU and muffler integration
- Trimming actuator integration

- Behavior under dynamic loads (uncertainty at this stage more than risk)

The reference aircraft where the FSHTP has been implemented for maturation and evaluation is representative of a mid-sized commercial aircraft, corresponding to the baseline for the Clean Sky 2 project. Throughout this document, the reference aircraft will be denoted as “REF”. In order to isolate pure configuration effects for the comparison of solutions, the same technology level is assumed for both the reference and the new configurations, with no “exotic” features accounted for to mitigate risks or exploit opportunities. The FSHTP Rear Fuselage and Empennage (RFE) concept shall provide the same Stability and Control (S&C) characteristics and respect the same payload constraints as the reference. The methodologies to quantify and compare the driving performance parameters (weight and drag) are the same and applied under the same assumptions on both configurations.

The FSHTP concept has been developed through an iterative process seeking to maximize the aircraft performance by;

- reducing the wetted area of the rear fuselage as much as possible
- reducing VTP and HTP size as far as allowed by Handling Qualities (HQ) criteria, exploiting favorable aeroelastic phenomena.
- seeking to improve Natural Laminar Flow (NLF) in the HTP as much as possible

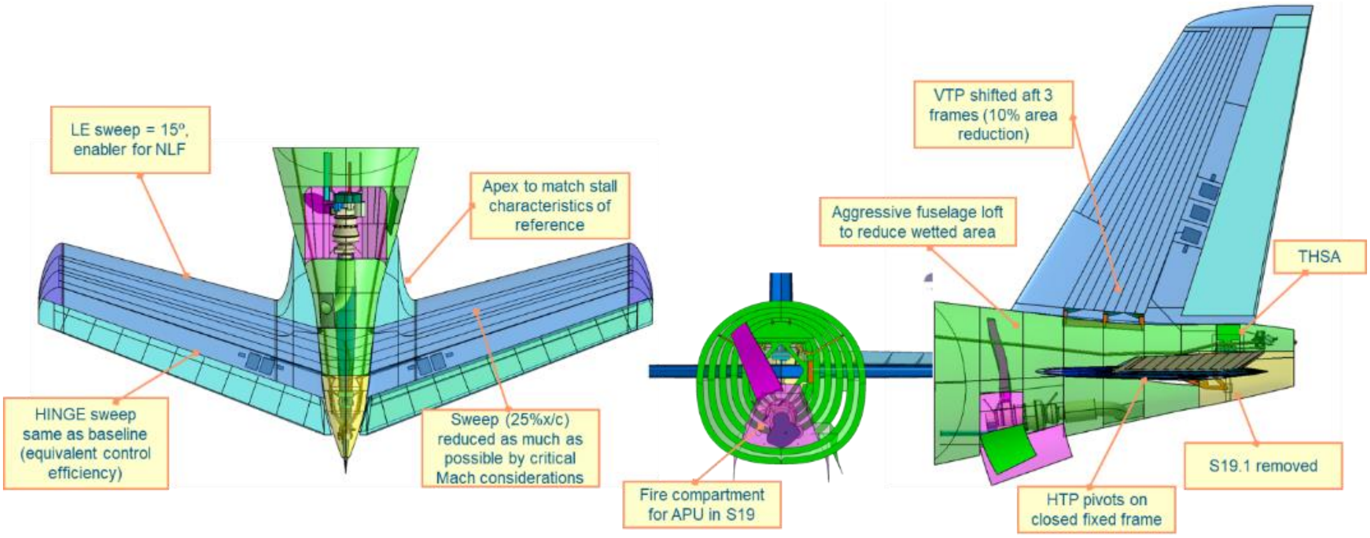


Figure 1 Key characteristics of the FSHTP concept

This document presents the work performed by Airbus in the ARE project. Additional work is being carried out in three other projects supporting ARE, namely:

- TAILSURF, dedicated to the experimental study of several types of leading edge undulated shapes and low drag large vortex generators, aeroelastic tailoring, plasma actuation and passive trailing edge aerodynamic devices. This project is led by Nottingham University with the University of Bristol and the University of Glasgow as partners.

- IMPACT [1], led by the Austrian Institute of Technology with the Universities of Napoli, Southampton and Udine, RTA of Vienna, AAC, CEST, Eurotech, Smart UP and Ansys Canada as partners, developing mid and high order MDO methods taking into consideration the aerodynamic effect of ice accretion for a range of leading edge shapes and coatings. The development of state of the art numerical methods for the prediction of ice-accretion taking into account the coating characteristics and their experimental and subsequent validation of the simulations in an icing wind tunnel are a key part of the project.

- MONNALISA, led by Politecnico de Milano with Metaltech Srl and Institut National de Recherche en Informatique et Automatique as partners, working on the development of low order non-linear aerodynamic methods to predict stall and maximum control power of a wide range of tail surface planforms, including experimental validation of CFD results.

A key enabler for the size reduction of the tail surfaces, particularly the horizontal tail, is the avoidance of ice accretion as a design consideration. In current practice the tail surfaces are assumed to be iced for the calculation of aerodynamic data for flight mechanics as it is generally considered impractical to use active systems to de-ice or prevent ice accretion on the empennage of high performance commercial aircraft. Therefore, passive means, either based on the use of coatings or configuration enabled, are sought to eliminate the aerodynamic penalty introduced by the ice accretion on the leading edge and are studied in various of the above mentioned projects. However, their work and results are not presented in this paper which focuses on configuration rather than on technology effects.

1.2 FSHTP Planform definition process

A theoretical increase of 7% in the isolated HTP rigid lift slope is possible with a change of planform, as shown below (Fig. 2). The actual installed aerodynamic behavior of the horizontal tail plane is influenced by the fuselage shape and Root Leading Edge Extension (LEX or apex). Flexible characteristics need to be taken also into account (favorable in the case of the FSHTP for stability considerations).

In this example, illustrating the steps required to evolve the reference HTP into the FSHTP presented in this paper, the sweep angle at mid chord is only reduced by 5.3º with respect to the reference (this parameter is indicative of the compressible behavior).

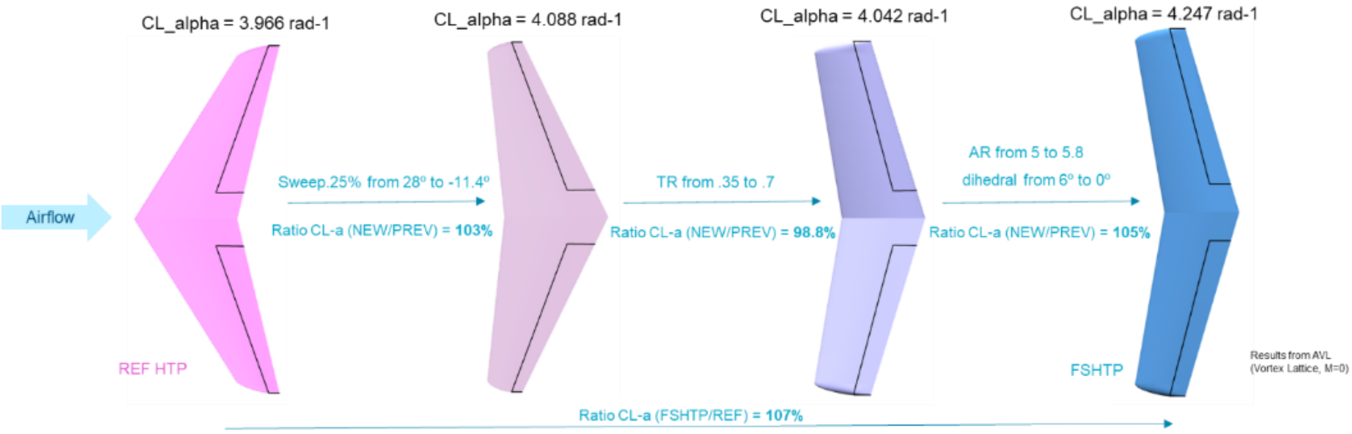


Figure 2 Planform evolution process

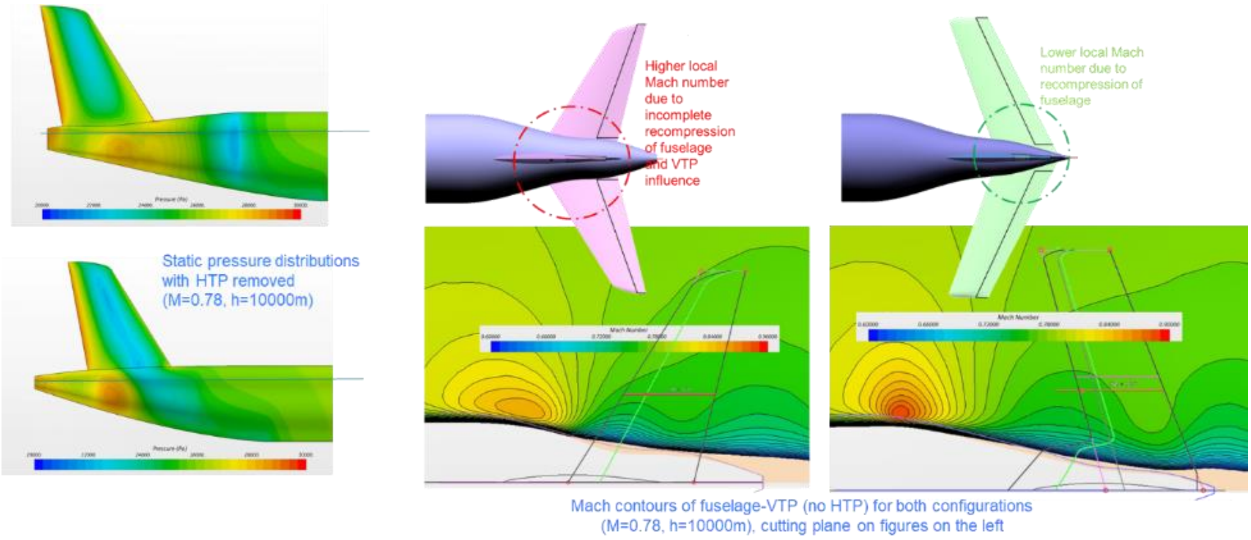
The unusually high Taper Ratio (TR), 0.7, of the FSHTP planform proposed can be understood by considering the spanwise load and Cl distribution on an AFT and FWD swept lifting surface:

- A conventional, aft-swept HTP with a TR=0.3 produces an approximately elliptical span load (local lift coefficient times local chord) distribution and a peak of Cl (local lift coefficient) towards the tip
- A FSHTP with TR=1 produces an equivalent span load distribution as the conventional, but with a peak Cl towards the root, moving the region of stall onset close to the fuselage, where it can be affected by a leading edge root extension.

2. Aerodynamic Analysis

2.1 Fuselage recompression effects on FSHTP high speed aerodynamics

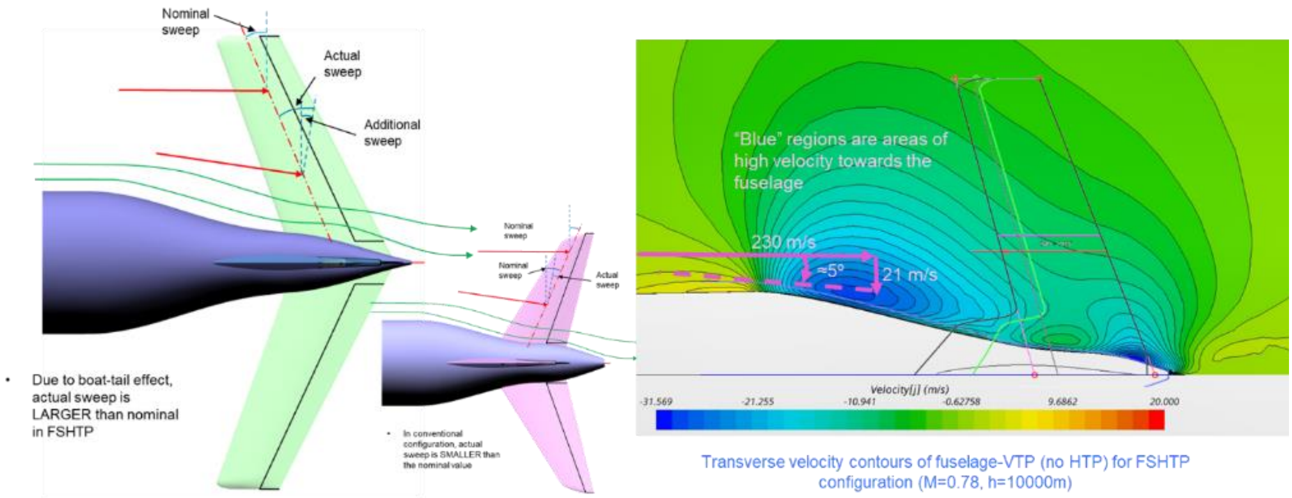
The more "aft" location of the FHTP root separates it from flow regions of higher local Mach number (Fig. 3). In principle this enables a smaller sweep angle for the same airfoil relative thickness (t/c). Local deflection of streamlines by the rear fuselage shape have the effect of increasing the effective sweep angle on the FSHTP configuration (with the opposite effect on the baseline) (Fig. 4). This is another enabler for a reduced sweep angle for the same t/c on the FSHTP concept.



Static pressure distributions with HTP removed (M=0.78, h=10000m)

Mach contours of fuselage-VTP (no HTP) for both configurations (M=0.78, h=10000m), cutting plane on figures on the left

Figure 3 Fuselage recompression effect



- Due to boat-tail effect, actual sweep is LARGER than nominal in FSHTP

- In conventional configuration, actual sweep is SMALLER than the nominal value

"Blue" regions are areas of high velocity towards the fuselage

Transverse velocity contours of fuselage-VTP (no HTP) for FSHTP configuration (M=0.78, h=10000m)

Figure 4 Fuselage boat-tail effect

On an FSHTP planform, with smaller chord length, Re (Reynolds number) and sweep angle, the possible laminar flow benefit is expected to be higher and more robust than in the reference configuration. At this stage of the project, the actual benefit in terms of NLF is assumed, its calculation pending until the configuration is fully evolved.

2.2 Longitudinal Stability and Control Characteristics

In order to perform a parametric exploration of the aerodynamic characteristics of the configuration, a High Order analysis tool is required. In this case a RANS CFD code has been used for the rapid exploration of the concept.

The CFD results are known to be acceptable for drag at high speed but not so robust on absolute values at high lift coefficients. However, trends are deemed reasonable even with highly separated flows, based on past experience. A large number of onglets (this is the round transition between the leading edge of tails and wings and the fuselage) and apex configurations have been explored in order to match the stall characteristics of the reference with a FSHTP (Fig. 5). A “normal” onglet results in very poor stall behavior therefore an apex is required in order to remove a LE separation at high angle of attack by generating a strong vortex and maintain lift to a comparable level as the REF.

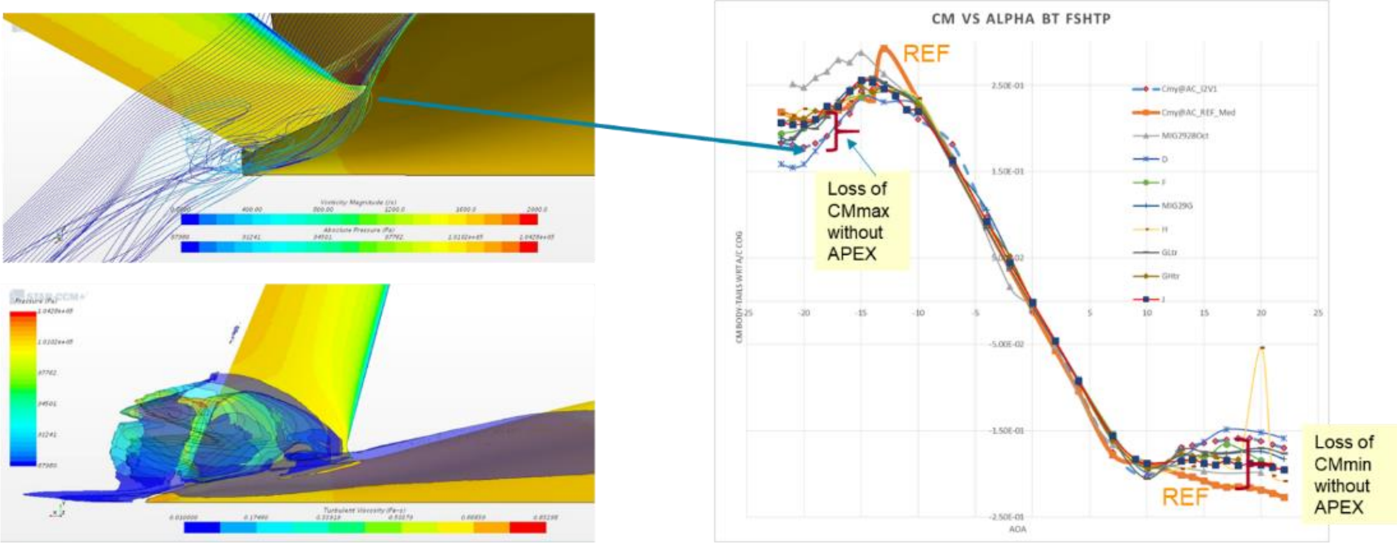


Figure 5 CM-alpha Body Tails (BT) for several APEX geometries studied

The calculated loss of rigid pitching moment slope of the “body tails” with respect to the reference is 3% for the FSHTP planform considered in this study, which is not critical for the handling qualities of the baseline aircraft and is partly recovered at low speed by flexible effects, as will be shown later.

As control power relies on the apex to provide sufficient lift capability, it must be ensured that this is protected from birdstrike. Taking a sideslip angle of 5º as a design condition, it can be geometrically shown that the apex is protected by the fuselage (Fig. 6).

The aerodynamic characteristics of tail planes are determined assuming “ice-on” conditions. An open question remains as to whether ice accretion will be detrimental on the proposed apex or this will be protected from icing due to the fuselage “shadowing effect”. This particular topic is being studied in detail in the IMPACT project with, at present, some indications that at least a significant part of the apex is actually protected from ice accretion.

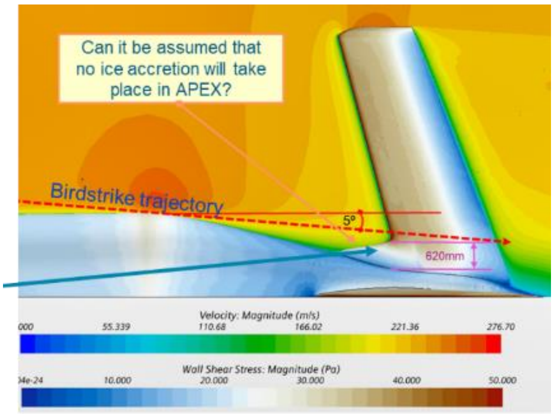


Figure 6 Apex and bird strike and icing considerations

Longitudinal maneuverability is partly determined by elevator efficiency (gradient of lift with elevator deflection) and control power (maximum lift with elevator deflected). The hinge line chordwise location and sweep angles are equivalent in both configurations, which should make efficiency the same in both cases. The elevator-to-fuselage gap with elevator deflected is more favorable (it closes) in the FSHTP, which should increase control power. The consolidation of these assumptions is part of the remaining work to do in this project.

2.3 Directional Aerodynamic Characteristics

Building on the physical insight provided by the CFD analysis of the baseline FSHTP configuration, a systematic series of geometry modifications and subsequent analyses has been performed in order to design the vertical tail plane (VTP) so as to match the target directional characteristics of the reference aircraft.

The initial VTP sizing approach is initially based on the assumption that the constant volume coefficient method is valid for sizing the VTP. A series of “body-tails” geometries with VTPs installed in different longitudinal positions and scaled according to the volume coefficient method has been generated and analyzed with a high order CFD method by the Future Projects department of Airbus Operations SL. The geometries have been adapted so that the vertical location (“z” coordinate) of each VTP is consistent with the shape of the fuselage (Fig. 7). The reference configuration has been used for this study with the goal of determining the validity of the sizing assumption.

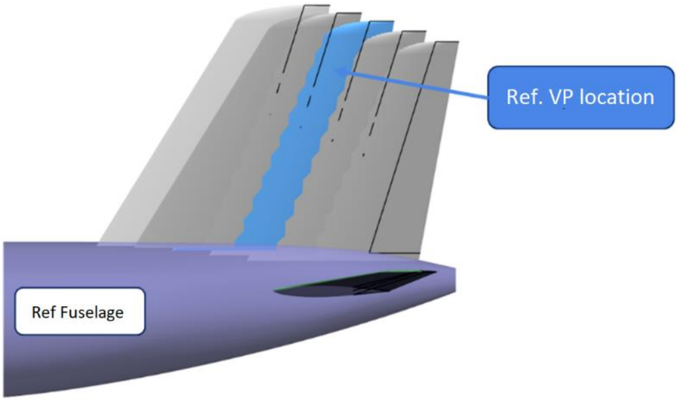
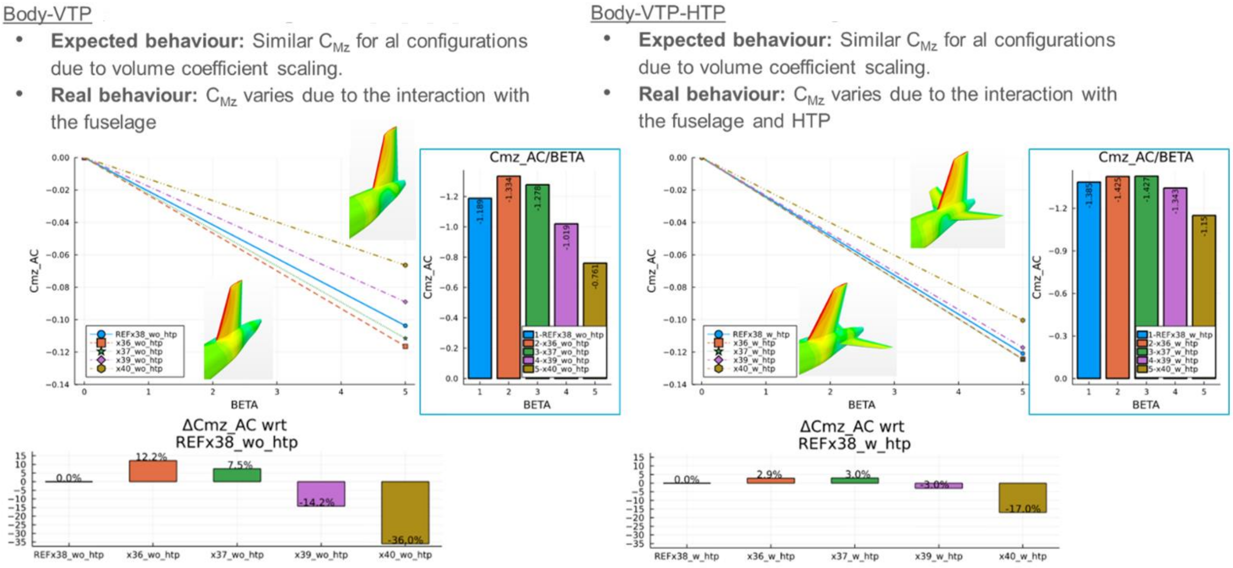


Figure 7. Systematic sweep of VTP longitudinal positions, cases studied


Body-VTP

- **Expected behaviour:** Similar C_{Mz} for al configurations due to volume coefficient scaling.
- **Real behaviour:** C_{Mz} varies due to the interaction with the fuselage

Body-VTP-HTP

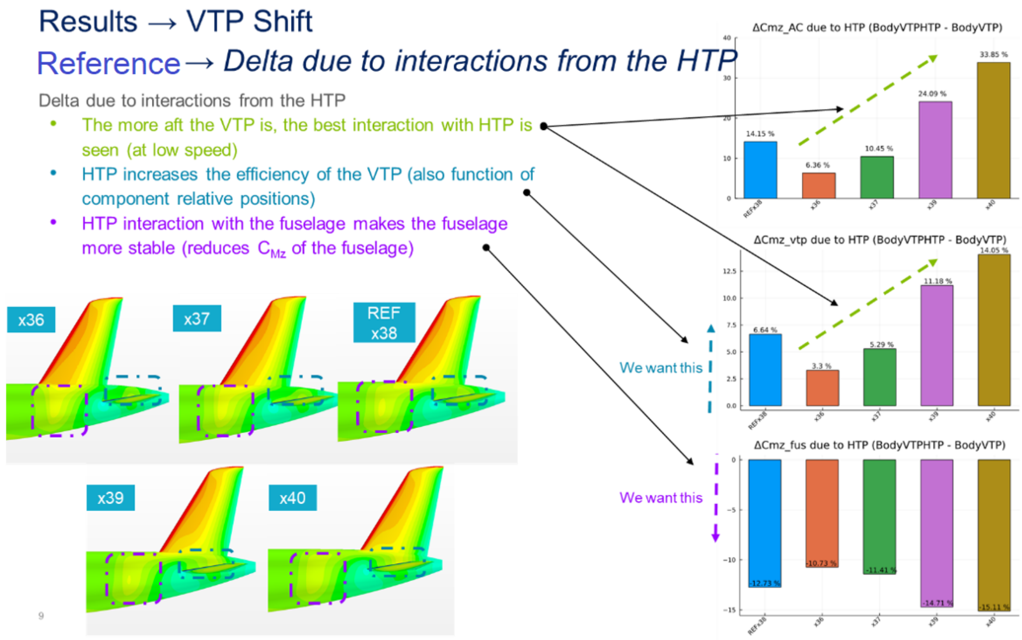
- **Expected behaviour:** Similar C_{Mz} for al configurations due to volume coefficient scaling.
- **Real behaviour:** C_{Mz} varies due to the interaction with the fuselage and HTP

Figure 8. FSHTP (left) and reference (right) models

The analysis of the body-VTP of the reference configuration shows a very significant reduction of the CN-beta (yawing moment coefficient derivative with respect to the sideslip angle) for positions of the VTP near the end of the fuselage (Fig. 8). This can be attributed to the loss of lateral projected area of the fuselage under the VTP which carries some loads induced by the fin. This loss in effectiveness more than exceeds the increase in lever arm due to the x-shift of the VTP position. This initially unexpected effect demonstrates the need for high order CFD analysis of configurations which depart significantly from the conventional, even when the departure is just a rather extreme location of a stabilizing surface as in this case.

The analysis of the body-VTP-HTP geometry for the same series of VTP x-shifts shows a much smaller loss or gain of effectiveness of the VTP, thus not departing significantly from the expected behavior resulting from the application of the constant volume coefficient approach, except for the aft-most position of the VTP.

This behavior can be explained by the end-plate effect provided by the HTP. The constructive interference compensates the loss of lateral area with the gradual restoration of a near-symmetric condition on the VTP aerodynamics. At the aft-most location of the VTP the interference is greatly reduced and the loss of CN_beta is of 17% with respect to the reference (Fig. 9).



Results → VTP Shift

Reference → *Delta due to interactions from the HTP*

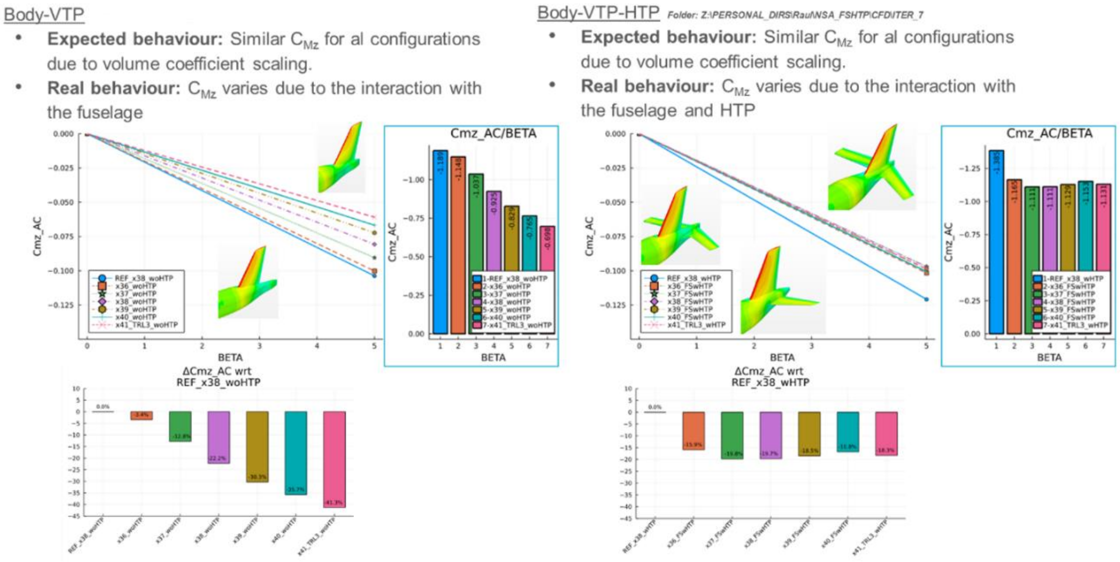
Delta due to interactions from the HTP

- The more aft the VTP is, the best interaction with HTP is seen (at low speed)
- HTP increases the efficiency of the VTP (also function of component relative positions)
- HTP interaction with the fuselage makes the fuselage more stable (reduces C_{Mz} of the fuselage)

Figure 9. CFD results for directional stability for the systematic position sweep in the reference configuration

Interestingly, on a conventional configuration with a traditionally located HTP, the application of the volume coefficient method does not result in excessive error for small variations around a “reasonable” location of the VTP.

An equivalent analysis of the FSHTP configuration results in the confirmation (even with an increased effect) of the loss of directional stability at iso-volume coefficient (Fig. 10). The addition of the forward swept HTP in the analysis modulates the loss of efficiency of the VTP for the aft-most locations of the VTP, but it is apparent that, in the configuration under study, there is a loss of CN_beta of around 18% (Fig. 11). This can be explained by the fact that the initial FSHTP configuration was designed only under considerations of longitudinal stability and control characteristics and the fuselage was thus shaped for minimum drag and weight, assuming the validity of the constant volume coefficient approach for the VTP.



Body-VTP

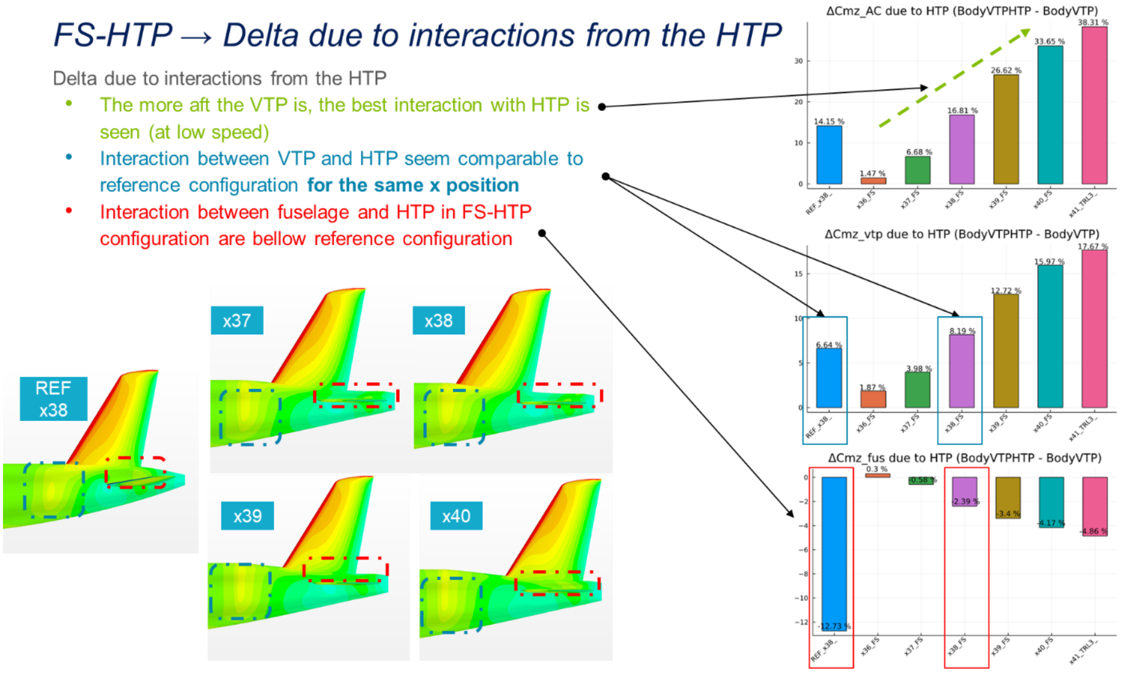
- **Expected behaviour:** Similar C_{Mz} for al configurations due to volume coefficient scaling.
- **Real behaviour:** C_{Mz} varies due to the interaction with the fuselage

Body-VTP-HTP *Folder: Z:\PERSONAL_DIRS\Rau\NSA_FSHTP\CFD\ITER_7*

- **Expected behaviour:** Similar C_{Mz} for al configurations due to volume coefficient scaling.
- **Real behaviour:** C_{Mz} varies due to the interaction with the fuselage and HTP

Figure 10. Comparison of sensitivity of yawing moment derivative for fuselage+VTP and fuselage+VTP+HTP

It can be noticed from the representations shown of this baseline FSHTP geometry that the fuselage tapers significantly aft of the rear pressure bulkhead, particularly on the top sides. This is precisely the reason that explains the loss of directional efficiency of the configuration as the reduction in lateral projected area between the base of the VTP and HTP is very significant compared with the baseline conventional configuration.



FS-HTP → Delta due to interactions from the HTP

Delta due to interactions from the HTP

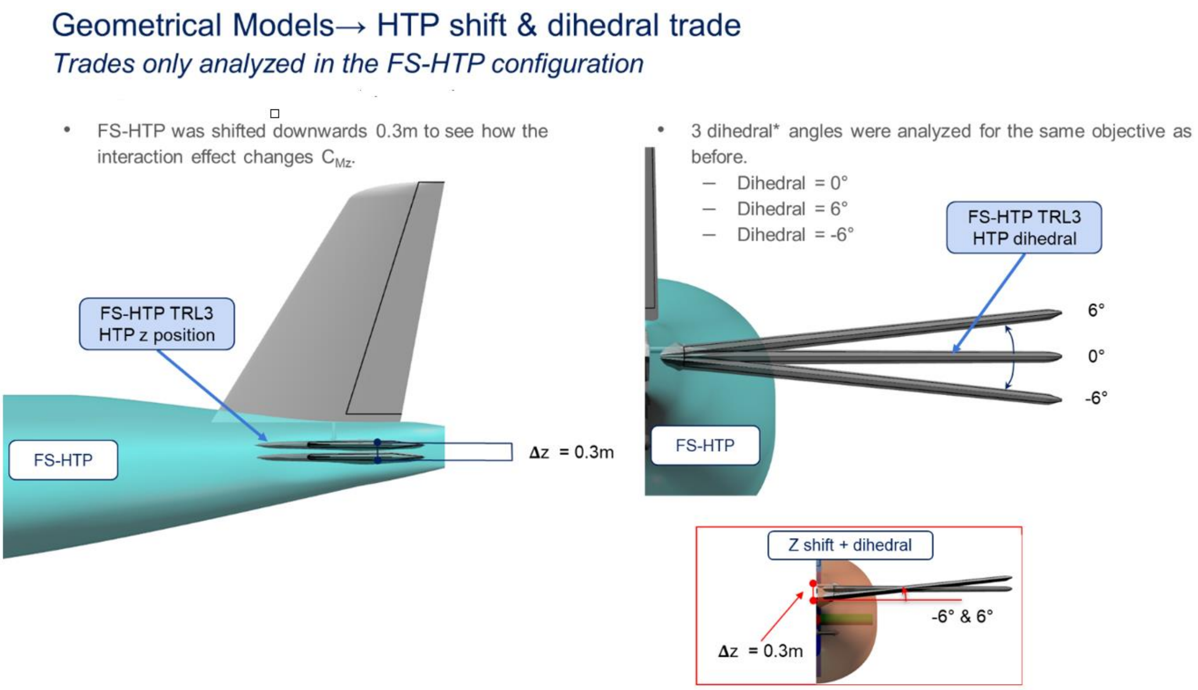
- The more aft the VTP is, the best interaction with HTP is seen (at low speed)
- Interaction between VTP and HTP seem comparable to reference configuration **for the same x position**
- Interaction between fuselage and HTP in FS-HTP configuration are bellow reference configuration

Figure 11. Effect of VTP-HTP interference in directional stability

In order to recover the target directional stability characteristics, additional modifications of the geometry are required. The baseline FSHTP configuration exhibits a zero dihedral HTP. This is enabled by the fact that tail strike of the FHTP tip at 5º of bank angle is avoided due to the geometry. The effect of the HTP dihedral angle on the directional stability has been studied by running two analyses with dihedral angles of 6º and -6º (Fig. 12). Additionally, since it has been proven by previous analyses that the lateral projected area between the VTP and the HTP has a strong influence on CN_beta, a vertical shift downwards of the HTP has also been modelled and analyzed

(Fig. 13).

It must be noted that the combination of the negative dihedral and the downwards shift of the HTP may compromise the tail strike characteristics of the HTP and these modifications will require an increase of the upsweep angle of the rear fuselage which may increase the parasitic aerodynamic drag of the concept. The final refinement of the configuration will be carried out using MDO techniques.



Geometrical Models→ HTP shift & dihedral trade

Trades only analyzed in the FS-HTP configuration

- FS-HTP was shifted downwards 0.3m to see how the interaction effect changes C_{Mz}.
- 3 dihedral* angles were analyzed for the same objective as before.
  - Dihedral = 0°
  - Dihedral = 6°
  - Dihedral = -6°

Figure12. FSHTP, dihedral modification study

Results → HTP Shift Trade

FS-HTP

HTP Shift downwards

- The **downward shift** increases C_{Mz} by **≈7%**

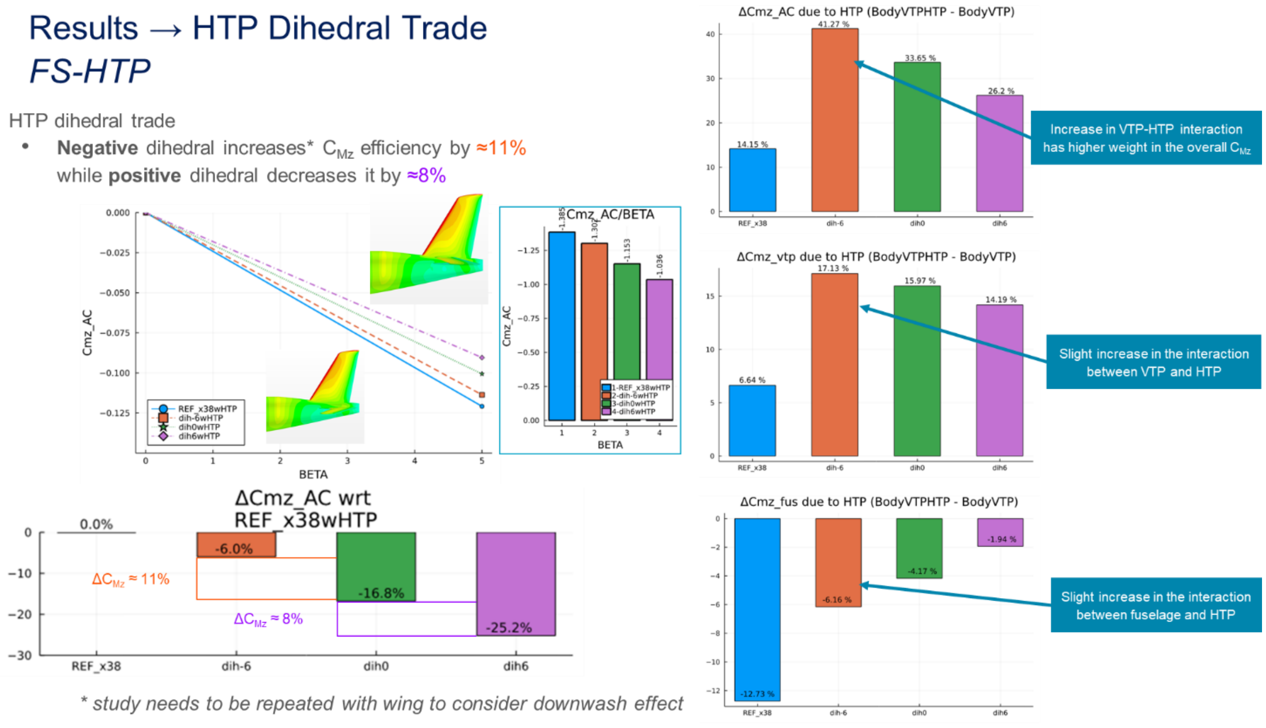
Reference configuration

Optimum according to VTP shift study

Optimum with HTP shift

The interaction between fuselage and HTP has been recovered

Figure13. FSHTP VTP shift trade study



Results → HTP Dihedral Trade

FS-HTP

HTP dihedral trade

- **Negative** dihedral increases* C_{Mz} efficiency by ≈11% while **positive** dihedral decreases it by ≈8%

* study needs to be repeated with wing to consider downwash effect

Increase in VTP-HTP interaction has higher weight in the overall C_{Mz}

Slight increase in the interaction between VTP and HTP

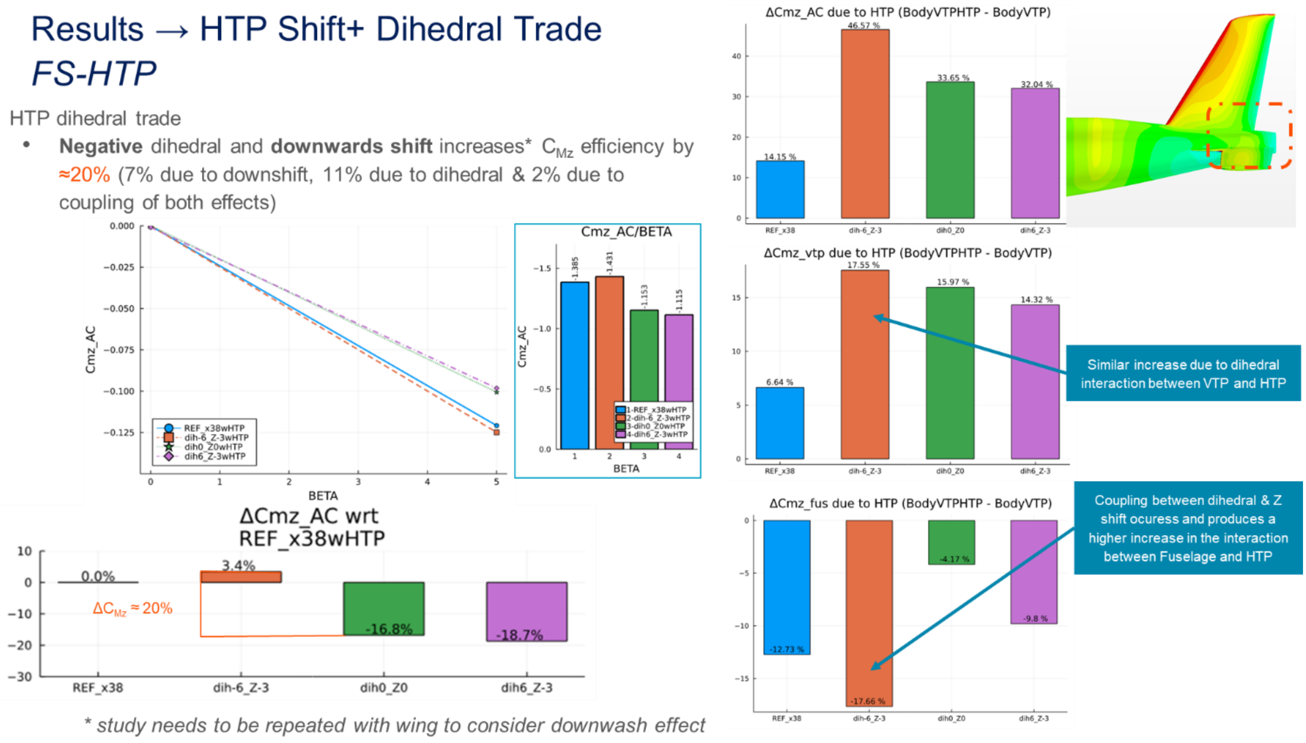
Slight increase in the interaction between fuselage and HTP

Figure 14. FSHTP isolated dihedral modification study

As shown in the figures above, the effect of a vertical, downwards, shift of the VTP by 0.3m is to increase the CN_beta by 7% on the baseline FSHTP geometry. This is very significant and proves the hypothesis of the effect of the portion of the rear fuselage between HTP and VTP in the directional stability.

The isolated effect of a FSHTP dihedral of -6º on CN_beta is to increase this coefficient by 11% (Fig. 14). Again, this is a very significant effect which physical cause is not so straightforward to explain. It is hypothesized that the effective lateral projection of the HTP contributes in a positive manner but that also the interaction between the suction side of the VTP and the upper surface of the HTP (generally a pressure side) is reduced, hence increasing the effectiveness of the VTP.

As these effects are highly coupled their effect cannot be superimposed directly. A new geometry combining both effects has been analyzed resulting in an increase of CN_beta of 20% (Fig. 15). At this point it can be assumed that the directional stability and control have been restored but it remains to confirm that the new geometry is feasible in terms of both internal volume and tail strike as well as to obtain a new value of the drag coefficient.



Results → HTP Shift+ Dihedral Trade
FS-HTP

HTP dihedral trade

- **Negative** dihedral and **downwards shift** increases* C_{Mz} efficiency by ≈20% (7% due to downshift, 11% due to dihedral & 2% due to coupling of both effects)

Similar increase due to dihedral interaction between VTP and HTP

Coupling between dihedral & Z shift ocuress and produces a higher increase in the interaction between Fuselage and HTP

* *study needs to be repeated with wing to consider downwash effect*

Figure15. FSHTP, combined HTP vertical shift + dihedral effect

3. Structural Analysis: Weight and Stiffness

3.1 Finite Elements Model Generation and Target Loads Setting

For the assessment of the impact on the component weight of the new geometry and methods, updated Finite Element models have been created of both the baseline and FSHTP concepts.

In order to provide a consistent basis for comparison of weights and stiffness of the two configurations, the reference aircraft maximum HTP and VTP forces and rear fuselage torque are taken as targets for the sizing of the reference aircraft RFE structure using preliminary structural sizing methods. A total of 7 “Unit” cases are specified in NASTRAN SOL144 (linear static aeroelastic solution) with nominal angles of attack and sideslip as well as control deflections. As the aerodynamic loads are proportional to dynamic pressure for a given flight Mach number, this is the parameter used to match the target loads on a sized reference RFE.

The pitch and yawing moments obtained from the NASTRAN solution of the reference aircraft around its center of gravity (CoG) will be taken as targets to size the FSHTP RFE (Fig. 17). This assumes that the new configuration will produce the same “restoring” effect on the aircraft, which is acceptable in static balance conditions but unclear once dynamic response is taken into account, this point being under current investigation.

The Global Finite Elements Model (GFEM) generation process is summarized in the diagram of figure 16.

In general, higher dynamic pressures are required in the REF model to attain the target loads, indicating a higher aeroelastic efficiency of the FSHTP (in itself, this is a risk as it creates an uncertainty on the loads assumptions)

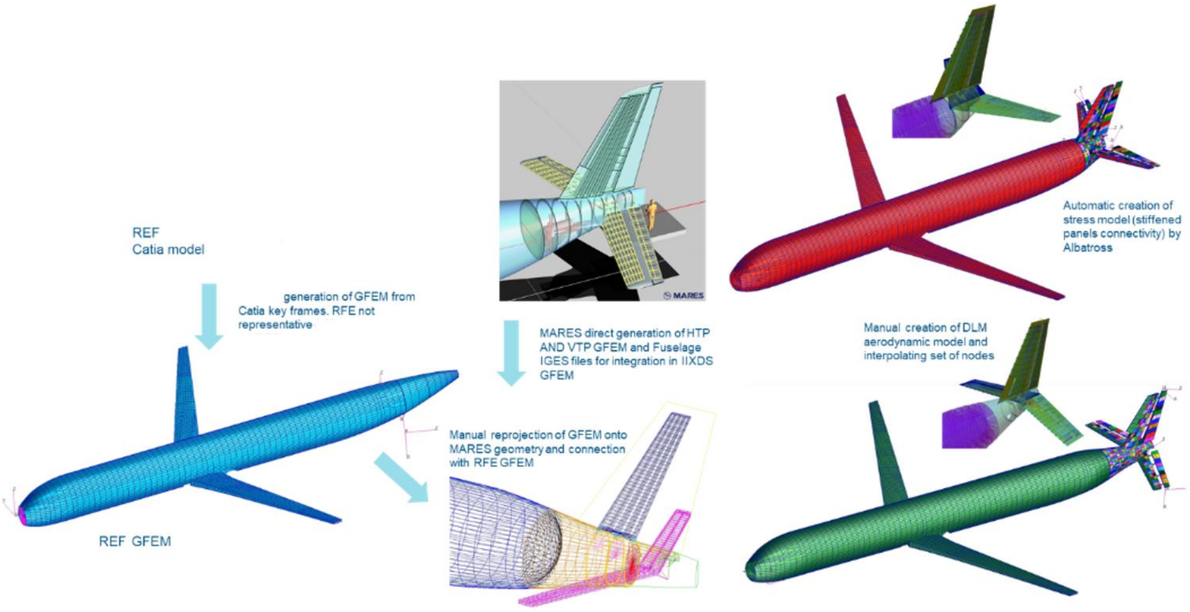


Figure 16 GFEM generation process

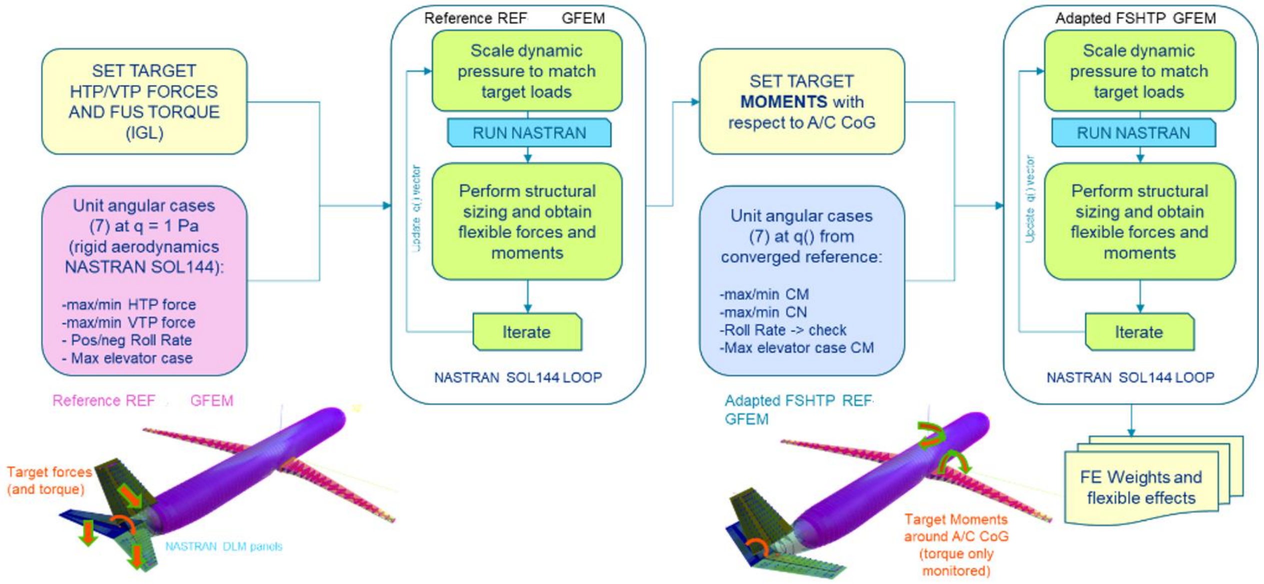


Figure 17 Loads generation for structural sizing

3.2 Structural Sizing Results and Weights (REAR FUSELAGE)

A complete structural sizing process of the rear fuselage and empennage has been carried out for both the reference and FSHTP concepts, using the same methods and target loads.

The process is illustrated in the following diagram (Fig. 18):

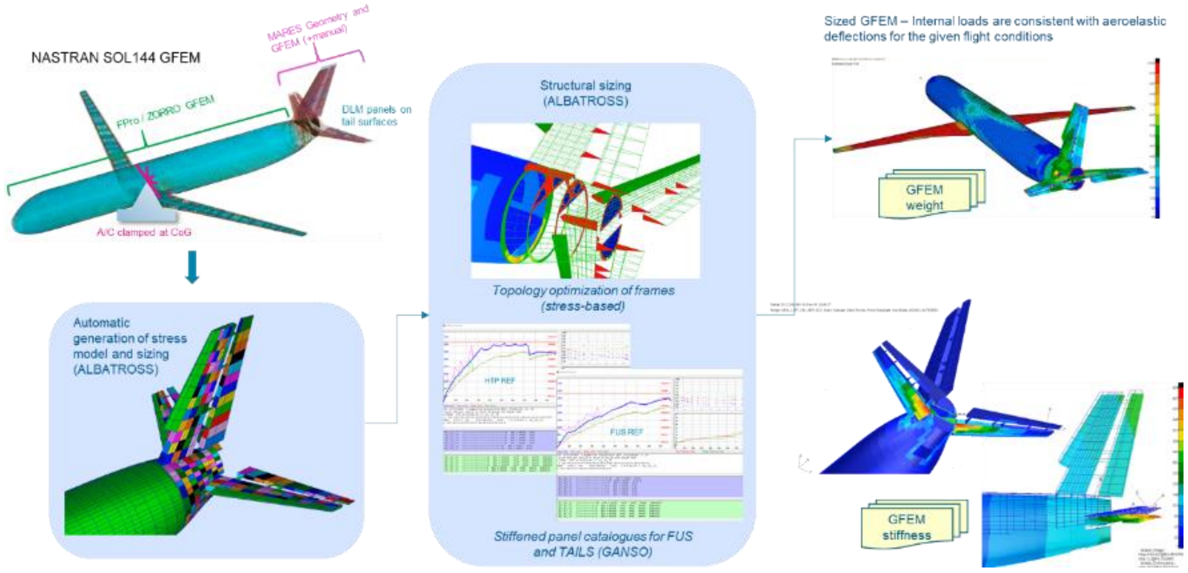


Figure 18 Structural Sizing Process

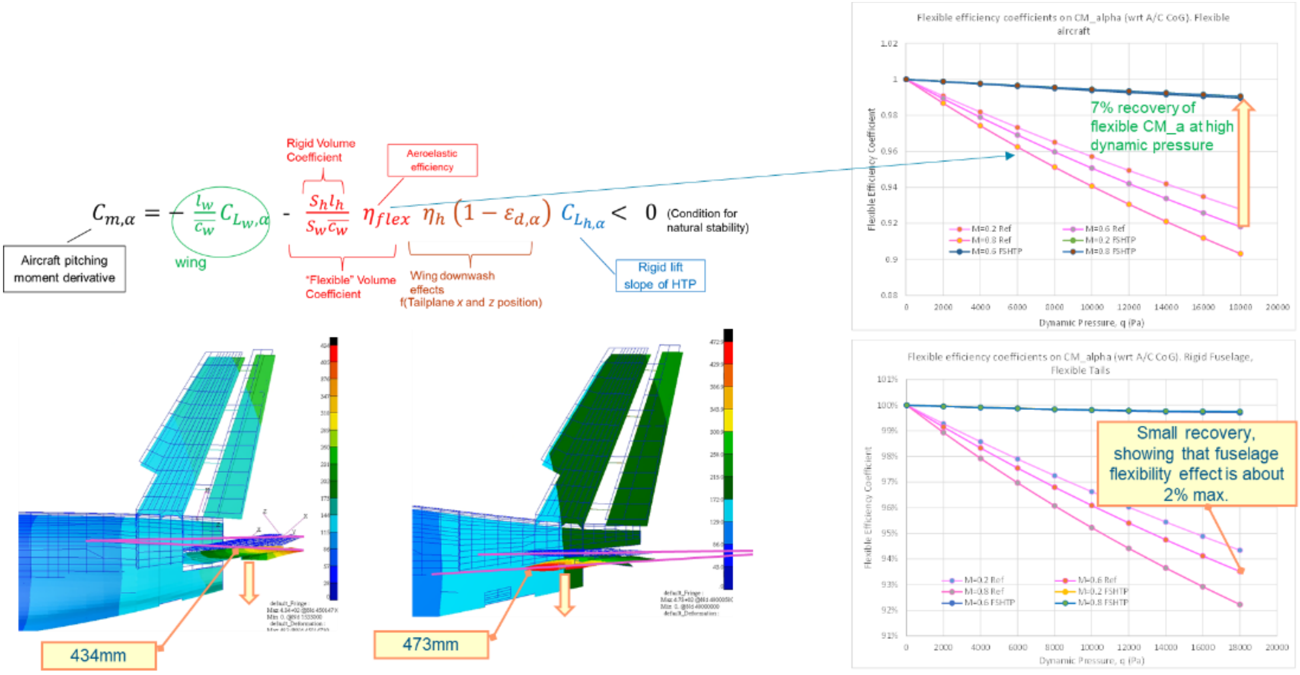


Figure 19 HTP Flexible aeroelastic efficiency

The structural sizing process is based on a catalogue-based optimality criterion method providing stiffened panels for the fuselage and tail planes with fully compatible laminates. During the course of the sizing iterations various consistency checks are performed automatically and local corrections are made where appropriate. The following features of the method can be highlighted;

- Forced symmetrization of the properties of the GFEM around the aircraft plane of symmetry to prevent "noise" due to the FEM topology
- Implementation of a discrete convolution function to guarantee feasible transitions of thickness properties
- Multi-spar web sizing using laminated stiffened panels design catalogues
- Use of multiple stiffened panel catalogues in the same sizing loop (enabling for example the definition of contiguous impact zones with different energy requirements)
- Ability to run different NASTRAN solutions in the same sizing loop (e.g., combining aeroelastic loads – the baseline- with inertial or static loads).

- The stiffened panel catalogue generation considers thickness-dependent CFRP strain allowables.

The sizing process runs in the Airbus mainframe computer and performs the complete sizing of the RFE with aeroelastic loads in about 10 minutes.

The loading process is the same as used previously, i.e., target aerodynamic forces are obtained from the known reference configuration and a NASTRAN SOL144 solution is run during the structural sizing loop in order to guarantee consistency of the loads and stiffness. The process requires a number of iterations on the flight conditions stated in the aeroelastic NASTRAN solution in order to match the target empennage aerodynamic forces. Then, the obtained moments around the center of gravity of the reference aircraft are taken as targets and the same process is repeated for the FSHTP configuration. FE weights are obtained per sub-component and non-structural weights are added, estimated and scaled from known reference data.

Some general statements can be made regarding the results of the sizing of both configurations;

- The FSHTP fuselage skin is thinner due to reduced load introduction by the VTP and the fact that the section is largely “closed” (although there are large cutouts on the lower shell in both concepts)

- Even though the FSHTP has a larger maximum deflection for the envelope HTP load cases, the flexural-torsional coupling induced by the forward sweep makes it more efficient aeroelastically (Fig. 19) and thus, a better stabilizing surface.

- The FSHTP structure requires generally higher thicknesses than the baseline HTP due to the reduction of the torsion box chord and absolute thickness near the root, even when the bending moment is reduced due to planform effects.

4. Overall Conclusions and Future Work

Integrating the results of the aerodynamic study and the structural sizing it can be stated that the FSHTP provides a Block Fuel saving between -0.6% and -0.7% at aircraft level ***from configuration only*** with remaining risks and opportunities to be studied in the final part of the ARE project.

A very large body of work is being performed in Clean Sky 2 “Advanced Rear End” project by various consortia from academia and industry. The results of this ongoing research may provide additional opportunities for the FSHTP stemming from the following lines work:

- Improved icing performance due to shadow effects on the leading edge extension and the use of advanced anti-ice coatings
- Aeroelastic tailoring opportunities specific to the FSHTP concept
- MDO optimization of the configuration and aerodynamic shapes

Various lessons learnt so far in this project are worth mentioning, specifically;

- The very large sensitivity of directional derivatives to seemingly secondary details in the rear fuselage and empennage design needs to be taken into account in the preliminary design phases
- The “Volume coefficient method” for VTP sizing has to be used with great caution
- The HTP dihedral effect has a large influence in the directional stability characteristics
- The HTP “z” position and area of rear fuselage between HTP and VTP is of great importance as well regarding the lateral aerodynamic characteristics of the configuration
- RANS CFD coupled with a rapid geometry generation tool is essential to perform these kind of

studies early on in the design process

- GFEM sizing using aeroelastic loads is a fundamental tool to properly capture the stiffness-loads interactions and obtain automatically the flexible efficiency of the component.
- The lessons learnt and new capabilities arising from this study will be extremely useful for the development of any kind of configuration of rear fuselage and empennage of future aircraft of this category.

5. Acknowledgements

This work has been partially funded by the “Advanced Rear End” project, part of the Clean Sky 2 European research programme.

6. Contact Author Email Address

Corresponding author mailto: raul.c.llamas@airbus.com

7. Copyright Statement

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