Preliminary Definition of an Aerodynamic Configuration for a Reusable Booster Stage within Tight Geometric Constraints

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ABSTRACT / RESUME
This paper describes the preliminary definition of the aerodynamic shape of a reusable booster stage. The partially reusable space transportation system under study consists of dual booster stages, which are attached to the expendable Ariane 5 core (EPC) at an upgraded future technology level. As a basic requirement of the study the overall dimensions and the position of all attachment points of the expendable part are not to be changed from today’s data. The paper describes in detail the geometric constraints of the ASTRA booster and the definition process for its preliminary outer aerodynamic shape. It is shown why canards have to be implemented. Finally, the preliminary aerodynamic coefficients are critically assessed with respect to the more sophisticated analysis by CFD and wind tunnel measurements.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>A</td>
<td>Area</td>
<td>m²</td>
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<tr>
<td>D</td>
<td>Drag</td>
<td>N</td>
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<tr>
<td>M</td>
<td>Mach-number</td>
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<td>l</td>
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<td>m</td>
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<td>q</td>
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<td>v</td>
<td>velocity</td>
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<tr>
<td>α</td>
<td>angle of attack</td>
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</tr>
<tr>
<td>ϕ</td>
<td>angle of leading or trailing edge</td>
<td></td>
</tr>
<tr>
<td>γ</td>
<td>flight path angle</td>
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<td>η</td>
<td>control surface deflection angle</td>
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SUBSCRIPTS, ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<tr>
<td>EAP</td>
<td>Etage d’Accélération à Poudre (of Ariane 5)</td>
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<td>EPC</td>
<td>Etage Principal Cryotechnique (of Ariane 5)</td>
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<td>ESC-B</td>
<td>Etage Supérieur Cryotechnique (of Ariane 5)</td>
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<td>GLOW</td>
<td>Gross Lift-Off Mass</td>
</tr>
<tr>
<td>H2K</td>
<td>Hypersonic Wind Tunnel (at DLR Cologne)</td>
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<tr>
<td>HC</td>
<td>Hydro-Carbon</td>
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<tr>
<td>JAVE</td>
<td>Jupe AVant Equipée (forward skirt of Ariane 5)</td>
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<tr>
<td>LFBB</td>
<td>Liquid Fly-Back Booster</td>
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<tr>
<td>LH2</td>
<td>Liquid Hydrogen</td>
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<td>LOX</td>
<td>Liquid Oxygen</td>
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<tr>
<td>MECO</td>
<td>Main Engine Cut Off</td>
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<tr>
<td>RLV</td>
<td>Reusable Launch Vehicle</td>
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<td>TMK</td>
<td>Trisonic Test Section (at DLR Cologne)</td>
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<tr>
<td>TVC</td>
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<tr>
<td>cog</td>
<td>center of gravity</td>
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<td>cop</td>
<td>center of pressure</td>
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1 INTRODUCTION

A reusable booster stage dedicated for near term application with an existing expendable core is under investigation within the system studies of the German future launcher technology research program ASTRA. To date, analysis shows that such a winged fly-back booster in connection with the unchanged Ariane 5 expendable core stage is technically feasible and is a strong competitor to other proposed reusable and advanced expendable launchers.

The basic design philosophy of the reusable booster is to choose a robust vehicle which gives a relatively high degree of confidence to achieve the promised performance and cost estimations. In as far as it is possible the applicability of existing and already qualified parts should be assessed for integration in the booster stage. The most recent design configurations of the reusable stage are described in references 1 and 2.

2 CONSTRAINTS IN THE DESIGN OF A SEMI-REUSABLE LAUNCH VEHICLE

The examined partially reusable space transportation system consists of dual booster stages which are attached to the expendable Ariane 5 core stage (EPC) at an upgraded future technology level. The EPC stage, containing about 185000 kg of subcooled propellants, is assumed to be powered by a single advanced derivative of the Vulcain engine with increased vacuum thrust. A new cryogenic upper stage (ESC-B) should include a new advanced expander cycle motor of 180 kN class (VINCI) at the end of the decade. Although different LOX-HC propelled booster configurations have been assessed [3], the ASTRA reference LFBB is to use cryogenic LOX-LH2 to enable similar engines on core and booster.

Two symmetrically attached reusable boosters, replacing the solid rocket motors EAP in use today, accelerate the expendable Ariane 5 core stage (Figure 1). A very basic assumption of the ASTRA study up to now has been that the size and attachment positions of the existing expendable parts of Ariane are not to be changed. The
The major intention of this supposition is to focus development on the reusable part and to probably save on development cost. Obviously, this postulation has a strong impact on the design choices for the reusable booster stage.

As a next fundamental design selection the LFBB's fuselage and outer tank diameter is chosen for 5.45 m so as to achieve a high commonality with Ariane's main cryogenic EPC stage. Other options had been addressed but were not offering significant advantages [4]. The propulsion of the reusable booster stage is based on the same advanced version of the EPC's Vulcain engine, but employs an adapted nozzle with reduced expansion ratio. Three engines are installed in a circular arrangement at the aft of each vehicle. The early baseline configuration of the LFBB as defined by DLR-SART in 2001 is shown in Figure 2 and Figure 3.

The intention of this simple shape was to check on the feasibility of component (e.g. tank) integration and to enable the start of the iterative design process. Obviously, the aerodynamic lay-out is neither optimized nor the booster's flyability is verified in the complete flight regime.

It is mandatory to aim for dual launch capability to achieve competitive specific launch cost if it is tried to reuse the Ariane 5 core stage. As the LFBB is proposed to replace the powerful EAP solid rocket motors, the future semi-reusable variant should at least reach similar payload performance to be attractive. Taking all these important programmatic considerations into account, the LFBB propellant mass should be maximized. However, the already mentioned geometric restriction on the unchanged length and attachment positions of the EPC limit the available tank volume. For operational reasons the RLV stage's nose should not hamper access to the payload section. Further, it is not allowed for the aft section to considerably exceed the exit plane of the core stage engine to avoid engine plume interaction.

Different propellant loadings and arrangements have been investigated and an evolved booster version (Y-6), very similar to Y-3 but with its length reduced by 2 m, has been introduced [4]. That variant with 164 Mg of nominal ascent propellant has been used as the starting point for the detailed aerodynamic design.

The LFBB requires trimmed aerodynamic datasets for the complete return flight trajectory between $0.27 < M < 7$ and angles of attack of $5° < \alpha < 35°$. The maximum structural loads at nominal reentry are defined at $n_z = 3.5$ g and $q = 60$ kPa.

The masses and components with a potentially variable position and those with a fixed position on the LFBB are identified to check options for moving the center of gravity (cog) and the center of pressure (cop). The components with variable position in axial direction (but always restricted with respect to individual functional requirements) are:
- Three air-breathing engines for fly-back,
- several small subsystems or pressurant tanks,
- the fuel required for fly-back,
- and (slightly) the main wing.

The components with a (more or less) fixed axial position are:
- The nose,
- the forward attachment ring,
- the main rocket propellant tanks,
- the vertical fins,
- the aft fuselage and thrust frame,
- the main rocket engines, and
- the body flap.
AERODYNAMIC DESIGN PROCESS

The LFBB aerodynamic surfaces have to provide sufficient lift at hypersonic atmospheric entry to stay within the load constraints. The optimum subsonic lift-to-drag ratio should exceed 5 to limit the fly-back fuel consumption to tolerable levels. Moreover, trimming with acceptable flap deflections and the goal of longitudinal stability requires shifting the center of pressure into the region of the center of gravity, basically calculated for Y-6 at 62% of reference length.

Early investigation results indicated severe problems concerning longitudinal stability and trim for the configuration Y-6. It has been found that the trim of this vehicle is only possible for $M < 5.6$ and assuming an actually not achievable far backward position of the center of gravity, $\frac{x_{cog}}{l} = 0.75$. The required flap deflections in hypersonic flow are in the order of $\alpha = 30^\circ$ and more than $\alpha = -10^\circ$ for $M < 2$ [6]. These results were obtained with very large deflection of the wing flaps and a body flap simultaneously turned aside (see Figure 4).

Additionally, the configuration is highly unstable [6]. The main wing could not be moved further in noseward direction without seriously compromising the available propellant and hence the launcher performance. Based on these results it had been decided to investigate LFBB configurations with canards.

The LFBB variants investigated early have canards with unswept trailing edges and a leading edge sweep of $\phi = 60^\circ$. With view to the canard efficiency and controllability in subsonic flow, this sweep angle is chosen in order to establish leading edge vortices up to angles of attack for the canards of $\alpha = 15^\circ$ [6]. The final configuration Y-7 (Figure 6) has a slightly reduced planform area of $A_{ref} = 350 \text{ m}^2$ compared with the previous Y-6 obtained by minor changes of canard and wing size. These values proved fully sufficient for the reentry load constraints and controllability requirements while saving on the vehicle’s dry mass.

The detailed aerodynamic work has been carried out at DLR’s Institute of Aerodynamics and Flow Technology. The aerodynamic CFD studies are complemented by unstructured Euler simulations (DLR Tau-Code). The Euler calculations also cover the assessment of the aerodynamic interactions between the Ariane 5 core stage and the two LFBB’s during the ascent phase [6, 13]. Although these investigations are preliminary in that they neglect the shock-boundary layer interaction and in some early calculations the engine flow, the obtained pressure distribution is a valuable basis for the definition of the launcher layout.

The Y-7 vehicle with canards has been the basis for the definition of a first wind tunnel model. In the meantime this model has been thoroughly investigated in the DLR wind tunnels TMK and H2K (see Figure 7). The force measurements at Mach numbers between $0.6 < M < 7$ have been used to verify the aerodynamic approach. The experiments delivered valuable data for an update of the vehicle’s shape. A detailed description of the experimental results is given in ref. 8 and 12.
The analysis of the early Y-7-LFBB showed its robust behaviour concerning the trim. The comparison of the neutral point position and the center of gravity points to the main problem of configuration Y-7, its lack of longitudinal stability during the dominating sub-/ transonic cruise flight. This effect could not be discovered by the simple CAC and Hotsose analyses because it is the result of a complex interaction between canard and wing flow [6, 7, 9].

Therefore, the focus of succeeding work has been the definition of adaptations which enable to increase the static margin and to preserve the robust trim behaviour. A numerical and experimental analysis presented in reference 7 demonstrates that the canard most dominantly influences the static margin of the configuration. Based on these findings a refined aerodynamic configuration of the LFBB could be defined. The advanced design has a canard with an increased leading edge sweep of 65° and a trailing edge sweep enlarged to 22°. The size is reduced to 90% of the original projected area of 15 m². The vertical position and the axis of rotation are kept unchanged. Additionally, an asymmetric NACA 3408 airfoil is used for the canards. The planform of the large wing is kept unchanged but a ‘rear loading’ RAE 2822 airfoil is applied to increase static margin.

The wing of the most recent LFBB configuration Y-8 spans about 21 m and the exposed area is about 115 m². The nose is of ellipsoidal shape with a length of 6.7 m and the total LFBB length including body flap is 42 m.

The nose section is followed by an annular attachment structure. The structure for canard mounting and actuation is provided at the center of this attachment ring. The cylindrical tank is integral and with respect to the EPC core stage it has the same diameter, shorter length, and similar lay-out. LOX is stored in the upper portion of the tank, and is, separated by a common bulkhead from the first LH2 tank. The ascent propellant mass of Y-8 reaches 167500 kg when subcooled as this allows a density increase of LOX to 1240 kg/m³ and to 76 kg/m³ for LH2. The integral tank section is followed by the wing and fuselage frame section. The rocket engines are mounted on a conical thrustframe. Two vertical fins are attached to the upper part of the fuselage, and inclined at 45 deg.

LOX - tank
LH2 – tank #1
separation motors
turbo engines
LH2 – tank #2

A complete flight dynamics simulation of the atmospheric re-entry and fly-back trajectory is run. Lift-, drag-, and pitching moment coefficients with regard to canard and bodyflap deflection are used in combination with a calculation of center of gravity movement, to perform a flight dynamics and control simulation. The trimmed hypersonic maximum lift-to-drag ratio reaches a value of about 2.0. In the low subsonic and cruise flight regime trimmed L/D is slightly above 5.0. Hypersonic trimming is performed by the canards and supported by the RCS. A stable condition is achievable at least up to angles of attack of 35 degrees.

A quasi-optimal trajectory is found by parametric variation of the initial banking maneuver [10]. The return of the LFBB should start as early as possible, but is not allowed to violate any restrictions. The banking is automatically controlled to a flight direction resulting in a minimum distance to the launch site. After turning the vehicle, the gliding flight is continued to an altitude of optimum cruise condition.

Including 30% fly-back fuel reserves to take into account possible adverse conditions like head winds, the booster needs about 4.0 Mg hydrogen for its more than one hour return leg.
All data obtained from the aerodynamic analyses are subsequently used in a flight dynamic simulation of the reentry and return flight of the reusable LFBB stage. Ref. 14 shows that aerodynamic trimming and longitudinal controllability of the reusable stage in the complete descent flight regime is achievable with reasonable margins for the center of gravity position.

4 COMPARISON OF RESULTS FROM FAST PRELIMINARY ANALYSIS WITH CFD AND WINDTUNNEL DATA

The early search for an aerodynamic configuration and generation of preliminary data sets has been performed with the DLR program CAC 2.24 [4]. CAC is a powerful tool for extremely fast preliminary analysis of launcher’s and hypersonic vehicle’s aerodynamics. It is important to select a suitable homologous geometry. For these reasons CAC is very efficient in identifying and also in quantifying a general trend, but is not well suited to study slight differences between more or less similar configurations. Figure 10 compares aerodynamic coefficients of the first canard configuration Y-7 at M=4. Although CAC is based on no more than very simple basic geometry neglecting any interference, it is possible to obtain aerodynamic coefficient data in quite good agreement with wind tunnel (TMK) measurements and surface inclination (Hotsose) calculations. The maximum L/D of CAC is slightly too optimistic because interference drag is neglected.

Figure 10 demonstrates that results of much more time consuming CFD-calculations (Euler with DLR Tau-Code) are very similar to the rapid CAC computation. Despite similar assumptions on friction the maximum L/D is again too optimistic for CAC due to lack of information on interference drag.

![Figure 10: Comparison of Y-7 LFBB aerodynamic coefficients at M=4](image)

However, CFD (Euler or Navier-Stokes) analysis is nevertheless indispensable in preliminary design studies, keeping in mind the limited capability of CAC to model complex flow phenomena and aerodynamic interactions. The LFBB analyses shows that an aerodynamic configuration which seems to be promising in CAC is not always a workable solution after performing more detailed calculations (see section 3 on the canard-wing interaction). But every lay-out deemed as infeasible by the preliminary aerodynamic examination has no reasonable chance of realization. Therefore, the approach implemented in CAC is fully justified as it is much easier and more rapidly to operate and hence the assessment of rearrangements can be done extremely fast.

![Figure 11: Comparison of Y-8 LFBB aerodynamic coefficients at M=0.6](image)
5 CONCLUSION

A reusable cryogenic booster stage for Ariane 5's expendable core has been aerodynamically designed under tight geometric constraints. The reusable boosters are designed with the same external diameter as Ariane5's EPC, the large integral tank is of similar architecture, and the basic lay-out of Ariane 5's forward skirt JAVE is reused for the LFBB's attachment ring to continuously operate existing manufacturing infrastructure for the RLV assembly.

The additional requirement to keep the existing positions of the EPC attachment points unchanged severely restricts aerodynamic design options. The requirement to be trimmable in the complete return flight regime $(0 < M < 7)$ has nevertheless been fulfilled by a wing-canard configuration.

A first wind tunnel test campaign of the LFBB has been successfully concluded. Canard-wing interaction detected in subsonics by CFD and experiments forced a redesign of airfoils and the canard’s leading and trailing edges to get a neutrally stable behavior. The aerodynamic vehicle configuration with two large canards has been refined and the wing has been adapted to a supercritical airfoil. The early stability problem in the subsonic fly-back cruise regime has been considerably eased. Additional results indicate a potential for a further reduction in canard size which may lead to a LFBB configuration which is stable along the complete return flight which has a very robust trim behaviour. A return trajectory flight simulation further demonstrates that under realistic canard actuator conditions the LFBB is fully controllable by active means despite potential longitudinal instability.

A comparison of aerodynamic data sets generated with different numerical and experimental methods shows good agreement even for relatively simple calculation approaches. But it has to be acknowledged that an aerodynamic configuration which seems to be promising by fast and simple methods not always remains a workable solution after performing more detailed CFD calculations. Therefore, a need for each type of analysis (preliminary, complex CFD, and experimental) exists to obtain a reliable aerodynamic design.

6 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of those from the ASTRA joint industry-DLR team involved in the preliminary sizing of the Liquid Fly-Back Booster.

7 REFERENCES


11. Eggers, Th.: Aerodynamic Design of an Ariane 5 Reusable Booster Stage, Fifth European Symposium on Aerothermodynamics for Space Vehicles, Cologne, November 2004


Further updated information concerning the SART space transportation concepts is available at: http://www.dlr.de/SART