LONGITUDINAL STABILITY AND TRIM OF AN ARIANE 5 FLY-BACK BOOSTER

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$A_{can}$</td>
<td>canard planform area</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A_{ref}$</td>
<td>vehicle planform area</td>
<td>m$^2$</td>
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<tr>
<td>$A_{wet}$</td>
<td>wetted area</td>
<td>m$^2$</td>
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<tr>
<td>$C_{D,f}$</td>
<td>skin friction drag coefficient</td>
<td>[-]</td>
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<tr>
<td>$c_f$</td>
<td>skin friction coefficient</td>
<td>[-]</td>
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<tr>
<td>$C_L$</td>
<td>lift coefficient</td>
<td>[-]</td>
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<tr>
<td>$C_{L,a}$</td>
<td>slope of the lift curve, $\partial C_L/\partial \alpha$</td>
<td>[1/rad]</td>
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<tr>
<td>$C_p$</td>
<td>surface pressure coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$C_m$</td>
<td>pitching moment coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$l$, $l_{ref}$</td>
<td>body length (l=$l_{ref}$=42 m)</td>
<td>m</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
<td>[-]</td>
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<tr>
<td>$NS$</td>
<td>abbreviation for: Navier-Stokes</td>
<td></td>
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<tr>
<td>$x_S$</td>
<td>x-coordinate of the center of gravity</td>
<td>m</td>
</tr>
<tr>
<td>$x_N$</td>
<td>x-coordinate of the neutral point</td>
<td>m</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>angle of attack</td>
<td>[°]</td>
</tr>
<tr>
<td>$\eta_{BF}$</td>
<td>body flap deflection</td>
<td>[°]</td>
</tr>
<tr>
<td>$\eta_{can}$</td>
<td>canard deflection</td>
<td>[°]</td>
</tr>
<tr>
<td>$\phi_{LE}$</td>
<td>leading edge sweep angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$\phi_{TE}$</td>
<td>trailing edge sweep angle</td>
<td>[°]</td>
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Abstract

A the winged liquid fly-back booster (LFBB) is one of the partially reusable space transportation systems considered within the German future space launcher technology research program ASTRA. The regarded system consists of two booster stages, which are attached to the expendable Ariane 5 core stage at an upgraded future technology level. The main area of interest of the presented aerodynamic study is the return flight after the staging procedure which dominates the layout of the LFBB.

The present paper discusses the aerodynamic refinement of an existing LFBB design, focusing on its longitudinal stability and trim. Detailed aerodynamic parameter studies are performed based on Euler calculations. Force measurements and selected Navier-Stokes simulations confirm this approach. They point out that a LFBB configuration may be designed primarily based on Euler simulations. The discussion of the numerical results and their comparison with experimental results shows that it is possible to adapt the originally given LFBB proposal in a way that it allows a nearly indifferent flight along the complete return trajectory and that it additionally enables a very robust trim behaviour.

1. Introduction

The investigated LFBB will be symmetrically attached to the Ariane 5 replacing the two solid rocket motors in use today (Fig. 1). The aerodynamic layout is dominated by the return flight and therefore, it requires trimmed aerodynamic datasets for the complete flight trajectory between $M=0.27$ and $M=6.5$. The presented aerodynamic study is primarily based on unstructured Euler calculations with the DLR Euler- and Navier-Stokes code TAU for $M<2$. For $M>2$ the DLR surface inclination method HOTSOSE is applied. As shown in [1] and [2] both codes are well established for these kind of applications. Within the trim calculations which are performed using HOTSOSE and Euler results the skin friction drag is estimated based on the assumption of a turbulent flat plate as $C_{D,f} = c_f \cdot A_{wet}/A_{ref}$ [3]. Additionally, force measurements at Mach numbers between 0.6 < $M$ < 7 are performed in the DLR windtunnels TMK and H2K [4]. They are used to verify the aerodynamic approach for conditions without and with sideslip.

The first part of the paper briefly summarizes the aerodynamic findings discussed in [5]. They show the essential need of canards to increase the static margin and to enable the trim of the initial LFBB proposed in
The resulting vehicle (configuration “Y7”) is the basis for the definition of the wind tunnel model (Fig. 2) investigated in [4].

The second part of the paper discusses selected Navier-Stokes simulations of the wind tunnel model. These allow to extract viscous effects, sting effects and the influence of the Reynolds number on the aerodynamic coefficients. Additionally, the reliability of the aerodynamic layout primarily based on Euler calculations is confirmed.

Finally, based on the aforementioned findings and the proposals discussed in [7], an aerodynamic parameter study is summarized which allows to improve LFBB “Y7” in a way that it enables a nearly indifferent flight along the complete return trajectory and a very robust trim behaviour.

2. Aerodynamic Definition of LFBB “Y7”

The initial LFBB-design is the configuration “Y6” (Fig. 3). The vehicle has a length of \(l_{ref}=42m\), a span of \(b=21m\) and a planform area of \(A_{ref}=360m^2\). Due to structural reasons it is required to position the trapezoidal wing in the backward part of the vehicle. Taking into account the expected center of gravity position at \(x/g/l=0.62\) a very large static margin is obtained which results in severe trim problems. In [5] it is shown 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, \(x/g/l=0.75\). The required flap deflections in hypersonic flow are still in the order of \(\eta=30^\circ\) and more than \(\eta=10^\circ\) for \(M < 2\). These results are obtained with very large wing- and a body flaps with simultaneous deflection (Fig. 3). Additionally, the configuration is highly unstable for the required center of gravity at \(x/g/l=0.75\). Based on these results it is decided to introduce canards.

Within the corresponding layout process [5] the LFBB configuration “Y7” is derived which allows to consider the realistic position of the center of gravity at \(x/g/l=0.62\) and to limit the canard deflections to \(\eta_{can}=8^\circ\) for subsonic flow and less than \(\eta_{can}=5^\circ\) for super- and hypersonic flight conditions (Fig. 4). Main problem of the current configuration is the lack of longitudinal stability during the cruise flight at \(M<0.7\). The pressure distributions in Fig. 5 show that the high canard efficiency which is required to obtain small control surface deflections is responsible for this problem. An increase of the canard deflection drastically increases the lift of the canard but reduces the lift of the wing because the flow is directed below the wing (Fig. 6). Both phenomena together reduce the static margin in comparison to a vehicle without canard. This is a well known disadvantage of canards but on the other hand they enable to trim the configuration for a wide range of centers of gravity. Nevertheless, although future improvements of the aerodynamic shape should avoid this difficulty, the flight dynamic simulations in [8] demonstrate under realistic canard actuator conditions that configuration “Y7” is fully controllable. After all it is the first feasible LFBB layout and therefore, it is used as basis for the wind tunnel model (Fig. 2).

3. Influence of Viscous Effects on the Vehicle Layout

The results discussed in the present paper and in [5] and [7] are obtained based on Euler calculations and do not contain any viscous effects. The effects of the canard leading edge vortices on the control surface efficiency are only predicted because the used airfoils were slightly sharpened at the nose. It is well known that this gives a good approximation of the vortex strength and that it also enables to predict vortex bursting. The real vortex structure of course is not obtained. Therefore, prior to the application of the findings discussed above a comparison with the available force measurements in the DLR TMK [4] have to substantiate the Euler results with view to the efficiencies of canard and body flap as well as with view to ability to predict the static margin. Fig. 7 contains a comparison of the pitching moment coefficients. It is obvious that the Euler results are very close to the experimental ones. Additionally, the canard efficiency is sufficiently predicted. The corresponding control surface efficiencies (Fig. 8) are presented using the parameter \(\Delta C_m\) which is the change in pitching moment resulting from a canard- or body flap deflection. Especially for the angles of attack of \(\alpha<6^\circ\) the results show that the Euler calculations allow to predict the efficiencies of canard and body flap with good accuracy. With view to the static margin a similar result is obtained (Fig. 8). The discrepancy between the experimental and the numerical result is less than 1% of the vehicle length for the shown subsonic condition.

The pitching moment coefficients predicted by Euler calculations (Fig. 9) indicate that the static margin decreases with increasing angle of attack. The comparison of two Euler flow fields in Fig. 10 points out, that the reason is found in a shock induced separation on the upper surface of the wing [7]. A similar effect is obtained in supersonic flow. Also the oil flow picture in Fig. 11 shows a shock induced trailing edge flow separation. This separation could be responsible for the smaller static margin obtained in the comparison between experiments and Euler results (Fig. 12).

In order to focus on these phenomena Navier-Stokes simulations for wind tunnel condition as well as for the flight condition are performed. They also allow to extract the sting effects and to assess the Reynolds number effects on the aerodynamic coefficients. Another goal of
the investigation is to confirm that the Euler results do not differ significantly from the viscous ones obtained for free flight conditions. This would allow to avoid time-consuming viscous calculations in future layout studies. Due to the availability of oilflow pictures three supersonic conditions at M=1.7 are considered. These are the wind tunnel model with and without sting (TMK condition, Re=9.1x10⁶) and the free flight (no sting, Re=76.7x10⁶). The latter condition corresponds the real flight in H=23km. Due to the fact that the flow topologies in the available oilflow pictures did not depend on the introduction of transition trips the state of the boundary layer was always assumed to be fully turbulent [4].

The considered configuration was LFBB “Y7” with undeflected control surfaces (ηBF=0°, ηBF=0°).

The computed surface flow topologies agree rather well with the TMK measurement (Fig. 13 and Fig. 14). The size of the separation along the trailing edge of the wing lies within the uncertainty range found in three different oilflow experiments. Also the spanwise position Δs of the largest separation length and the flow topology at the wing tip are predicted. Fig. 14 shows that the separation on top of the sting and the stagnation point downstream of it are also properly captured. The comparison of the aerodynamic coefficients in Fig. 15 underlines the good agreement. In particular the computed coefficients for lift and pitching moment which are important to assess the static margin are very close to or inside the experimental uncertainty of Δα<0.25° [4].

One important goal of the viscous simulations is to verify the reduced static margin under wind tunnel conditions. Although the slope of the pitching moment curve ∂Cm/∂α of the Navier-Stokes results does not perfectly match with the one from the Experiment, the comparison of the numerical results, here windtunnel condition with sting and Euler, shows the same trend than previously shown in Fig. 12 namely, the Euler calculations predict a higher static margin than it is obtained under TMK conditions. As aforementioned, the reason is the trailing edge separation on top of the wing. If the Reynolds number is increased to free flight conditions the separation disappears and attached flow is obtained on top of the wing (Fig. 16). As discussed based on (Fig. 10) the attached flow on the wing results in an increased static margin. If now the results for the free flight condition and the Euler results are compared one sees that the ∂Cm/∂CL is almost identical because the viscous effects on the surface are obviously of minor interest with view to the static margin (Fig. 17). Fig. 18 shows that the flow topologies of the Euler and the Navier-Stokes calculations are similar with the exception of the upper surface of the canard. Here, for Re=76.7x10⁶ the starting appearance of leading edge vortices is predicted but the influence on the surface pressure distribution is negligible for the shown condition (Fig. 19).

Another not yet discussed effect obtained by the viscous calculations is the influence of the sting on the aerodynamic coefficients. A closer view into Fig. 15 points out that the sting is of minor interest with view to the dicussion of the static margin. The slopes ∂Cm/∂α for the cases with and without sting are very similar. But, the sting induces an additional pitch up. The surface flow itself is not affected by the sting (Fig. 20). The sting effect is limited to the vehicle base area on top of the body flap. The pressure distributions for this region (Fig. 21) point out that the sting is responsible for an increase of the pressure level. This results in the aforementioned additional pitch up moment.

A closer view to the computed drag coefficients shows that the Navier-Stokes solutions allow a good prediction of the introduced changes in flow condition and geometry (Fig. 15). First, the discrepancy of the drag coefficients for the case with sting is less than 3% in comparison to the experimental results. As expected, the configuration without sting has an increased drag coefficient because the pressure level on the base area decreases (Fig. 21). The increased Reynolds number again leads to a reduction of CD while the Euler values are smaller because they do not contain the viscous drag. In order to prove the strategy used for the trim results where the Euler computations were corrected with respect to the viscous effects using the skin friction drag of a turbulent flat plate, Fig. 22 compares these results with Navier-Stokes calculations. It turns out that the “Euler + turb. flat plate” value only differs 1% from the Navier-Stokes result for the free flight condition which proves the applied strategy.

The comparison of the numerical and the experimental results fully confirms the approach used to defined the shape of the LFBB configuration primarily based on Euler results. The discussion points out that the layout for the considered subsonic and supersonic conditions allows an adequate accuracy. For transonic conditions the approach still has to be proven based on the planned experiments for 0.8<M<1.3.

4. Parameters for the Adaptation of the Static Margin

In the following some proposals to increase the static margin of configuration “Y7” based on Euler calculations are going to be introduced. In order to obtain a good comparability the center of gravity is always assumed to be at xg/l=0.62. The body flap deflection is fixed as ηBF=5°. Adapted reference areas are given in the corresponding figures if required. In the comparisons of the neutral point and the center of gravity always
a fixed position of the center of gravity is considered. The additional indicators of the stable and unstable regions are only to allow a easier interpretation of the figures.

As shown by Fig. 5 and Fig. 6 a strong interaction between wing and canard is obtained for the cruise conditions at M<0.7. In order to get an idea about the influence of the vertical wing position with respect to the canard the original wing of configuration “Y7” was positioned in the midplane of the body directly into the water plane of the canard (Fig. 23). Main outcomes of the changed vertical wing position are an increased angle of attack, a reduced canard deflection and unfortunately, a slightly reduced static margin. The reason for this effect was already given by the pressure distribution in Fig. 6. Here it was shown that a canard deflection directs the flow below the wing. As a consequence of this a low pressure region is induced which reduces the wing lift and also the static margin. The same effect appears for the mid wing configuration. Due to the higher vertical wing position the flow is partially directed below the wing. This reduces the wing lift coefficient and also reduces the static margin. In conclusion the mid wing configuration has to be withdrawn because an additional reduction of the static margin is not acceptable. But the results point to the fact that it would be advantageous to keep the original low wing position in combination with a canard position at the top of the body. There it would accelerate the flow above the wing and an increase of the static margin would appear. Unfortunately, this version is not possible because the structural design of the attachment ring to the Ariane 5 is already fixed [8] and does not allow this adaptation of the canard position.

The current results show that the $C_{L,a}$ of the canard has to be reduced for an increased static margin while keeping its planform area to obtain canard deflections of $\eta_{can}<10\%$. Therefore, the planform shape of the canard is adapted keeping the planform area constant (Fig. 24). The leading edge sweep of the adapted canard is increased to $\phi_{LE}=65^\circ$ and the trailing edge sweep to $\phi_{TE}=22^\circ$. The increased sweep of the canard reduces its $C_{L,a}$ and shifts the appearance of leading edge vortices to higher angles of attack. The corresponding trim results are summarized in Fig. 25. As expected the canard deflections are slightly increased because of the reduced $C_{L,a}$ of the new canard planform. Due to the same reason the static margin is increased by 0.75% of $I_{ref}$. But despite of this gain the static margin is still $(x_N-x_S)/l=0.05$. Therefore, with view to the goal to keep the canard deflections as small as possible and to increase the static margin as much as possible the size of the adapted canard “can6522” was changed in a wide range. Two additional canards with 50% and 25% planform area are considered (Fig. 26). The vertical position and the axis of rotation are kept unchanged. The corresponding trim results (Fig. 27) point out that the influences on the canard deflection and the static margin are huge. First it is shown that even the 50% canard leads to a configuration which may not be trimmed. On the other hand it turns out that the canard is the dominating parameter to increase the static margin of the vehicle. The lower part of Fig. 27 shows that the 25% canard would allow an indifferent flight for M<0.7 but it does not enable the trim of the configuration.

Another option to increase the static margin is to shift the center of pressure of the wing backward. For unchanged planform area and aspect ratio this can be done by increased leading edge and trailing edge sweep angles. But this adaptation is technically not feasible because it requires an adaptation of the Ariane 5 launch pad. Therefore, the only alternative is the introduction of a rear loading airfoil. Here a RAE 2822 airfoil is chosen (Fig. 28). The trim results show that the canard deflections can be halved and for the dominating cruise flight at M=0.6 the static margin is increased by 1% of $I_{ref}$ (Fig. 29). The prize for this gain at M<0.7 is a reduced static margin for M>0.8 which results from the strong shocks in the backward part of the wing. But with view to the fact that the deceleration from supersonic flight to sub-/transonic cruise flight at M<0.7 is very short in comparison to the complete return flight, this disadvantage at M>0.8 may be accepted. A larger uncertainty to choose this airfoil is the super- and hypersonic part of the trajectory because in comparison to the flat lower surface of the original wing airfoil an important loss of lift in the backward region of the cambered lower surface of the RAE airfoil is expected. This could result in the situation that the trim of the vehicle is impossible for M>2. Fig. 30 points out that this is not the case for the present vehicle configuration. It can be seen that a moderate increase of the body flap deflection to values of $\eta_{BF}=12^\circ$ results in unchanged canard deflections. With the background of these additional findings the introduction of the new airfoil is promising because it allows to halve the required canard deflections.

Summarizing the sensitivity study it shows that the LFBB “Y7” unfortunately is very robust concerning most of the applied geometry changes. It is visible that the canard is the most dominating part to influence the static margin of the configuration. Nevertheless, the results are very promising because they open a great potential for the definition of a new configuration “Y8” based on the recollected results of the present chapter.
5. Definition and Analysis of an Enhanced LFBB “Y8”

With view to the definition of a new LFBB configuration the main findings of the previous discussion are:

- A canard with increased leading edge sweep but constant planform area allows to increase the static margin about 0.75% of $l_{ref}$. The increased canard deflection is acceptable.
- The RAE 2822 airfoil for the wing allows to halve the canard deflections and increases the static margin about 1% of $l_{ref}$ during the cruise flight at $M<0.7$.
- The size of the canard is the dominating parameter to stabilize the LFBB.
- The TMK experiments [4] point out that a body flap deflection of $\eta_{BF}=0^\circ$ is to prefer for the sub- / transonic cruise flight.

Other additional parameters to be taken into account for a new configuration are:

- The use of an asymmetric canard airfoil instead of the actual symmetric one. This allows a comparable lift of the canard but at smaller canard deflections.
- Additionally, the current status of the structural design [9] results in a center of gravity at $0.59 < x_S/l < 0.6$ during the sub- / transonic cruise flight.

The consequent application and superposition of these findings and facts results in the enhanced LFBB configuration “Y8” (Fig. 31). Configuration “Y8” has a canard with a leading edge sweep of $\phi_{LE}=65^\circ$ and a trailing edge sweep to $\phi_{TE}=22^\circ$. The size is reduced to 90% of the original size of 15m$^2$. The vertical position and the axis of rotation are kept unchanged. Additionally, an asymmetric airfoil is applied. The planform of the wing is kept unchanged but the previously considered RAE 2822 airfoil is applied.

The trim results for configuration “Y8” are summarized in Fig. 32. Here, a center of gravity at $x_S/l=0.60$ is assumed. In comparison to configuration “Y7” the results point out that the design loop is very successful. As expected for the reduced planform area of the canard and the new wing airfoil the resulting angles of attack of the configuration are slightly increased. During the cruise flight at $M<0.7$ the canard deflection is reduced to $\eta_{can}=3^\circ$. But the most important result is that the configuration “Y8” has a nearly indifferent behaviour for $M<0.8$ and at higher Mach numbers it is stable. The results additionally indicate a potential for a further reduction of the canard size which may lead to a LFBB configuration which is stable along the complete return flight enabling a very robust trim behaviour.

6. Conclusions

A complete aerodynamic design cycle for the improvement of an Ariane 5 liquid fly-back booster is introduced. The layout is performed based on Euler calculations using unstructured grids. The approach is verified based on force measurements in the DLR TMK facility and on selected Navier-Stokes calculations. The results point out that a design primarily based on Euler computations accurately predicts the canard- and body flap efficiencies and the static margin of the vehicle.

The study showed that the canard is the dominating parameter with view to the static margin of the vehicle. Additionally, the adaptation of the wing airfoil is promising. Recollecting all the findings of the study it was possible to define a new enhanced LFBB configuration “Y8”. This configuration allows an indifferent cruise flight at $M<0.8$ and is stable for $M>0.8$. The required canard deflections could be reduced to $\eta_{can}=3^\circ$ applying a new canard planform with increased leading edge sweep and an asymmetric airfoil. The small canard deflections additionally indicate a potential for a further reduction of the canard size which may lead to a LFBB configuration which is stable along the complete return flight enabling a very robust trim behaviour.

7. References


8. Figures

Fig. 1 Ariane 5 with liquid fly-back boosters

Fig. 2 Wind tunnel model of configuration “Y7”

Fig. 3 Initial configuration “Y6”

Fig. 4 Trim results for configuration “Y7”
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Fig. 6  Interaction of canard and wing, plane: y=4.5m

Fig. 7  Comparison Experiment / Euler: pitching moment coefficients

Fig. 8  Comparison Experiment / Euler: control surface efficiencies and trim results

Fig. 9  Influence of AoA on pitching moment $C_m$
Fig. 10 Influence of AoA on the flow field, conf. “Y7“

\[ M_\infty = 0.7 \]
\[ \eta_{BF} = 5^\circ \]
\[ \alpha = 10^\circ \]
\[ \eta_{can} = 0^\circ \]

\[ M_\infty = 0.7 \]
\[ \eta_{BF} = 5^\circ \]
\[ \alpha = 15^\circ \]
\[ \eta_{can} = 0^\circ \]

Fig. 11 Oilflow picture of the upper side of conf. “Y7“

\[ M=1.7 \]
\[ \text{turbulent} \]
\[ \text{Re}=9.1\times10^6 \]

Fig. 12 Comparison Experiment / Euler:

supersonic trim results

\[ x_N^* / l = 0.620 \]
\[ \eta_w=5^\circ \]

\[ x_N^* / l = 0.6 \]
\[ \text{Exp. TMK} \]

Fig. 13 Flow topology on the wing, conf. “Y7“

\[ M=1.7 \]
\[ \text{turbulent} \]
\[ \text{Re}=9.1\times10^6 \]

Fig. 14 Flow topology on the sting, conf. “Y7“

\[ M=1.7 \]
\[ \alpha=5^\circ \]
\[ Y7, \text{clean} \]
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Fig. 16 Influence of the Reynolds number on the surface flow topology

Fig. 17 Comparison of the pitching moment slopes
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Fig. 19 Influence of the boundary layer on the surface pressure coefficients

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Fig. 28 Influence of the wing airfoil, geometries
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Fig. 30 Trim results for the RAE 2822 airfoil, M>2

Fig. 31 Surface definition of configuration "Y8"