AERODYNAMIC DESIGN AND ANALYSIS OF AN ARIANE 5 LIQUID FLY-BACK BOOSTER

Th. Eggers; O. Božić

DLR, Institute of Aerodynamics and Flow Technology, Lilienthalplatz 7, 38108 Braunschweig, Germany

Abstract

Within the German future space launcher technology research program ASTRA two reusable first stage designs are under investigation. The one dedicated for near term application with an existing expendable core stage is called a winged liquid fly-back booster (LFBB).

The main goal of the present study is the refinement of an existing LFBB design. The regarded partially reusable space transportation system consists of two booster stages, which are attached to the expendable Ariane 5 core stage at an upgraded future technology level. The two main areas of interest of the study are the descent after the staging procedure and the ascent in the phase with maximum dynamic pressure. The descent dominates the aerodynamic design of the LFBB and the ascent limits the mission with view to aerodynamic and structural loads under changing atmospheric conditions.

The aerodynamic parameter studies pointed out that an LFBB may not be trimmed or stabilised without the introduction of canards as control surface. A detailed analysis of the flow field for the considered ascent condition points to some regions which have to be considered in more detail during the structural layout of core stage and booster.

1. Introduction

The aerodynamic and flight dynamic simulation applied in the second design loop of the LFBB requires trimmed aerodynamic datasets for the complete flight trajectory between 0.27 < M < 7 and angles of attack of 5° < α < 35°. Within these studies tight margin concerning longitudinal stability and trim have to be taken into account for the isolated LFBB as well as for the complete system (Fig. 1). Due to the structural design of the Ariane 5 core stage the position of the LFBB with regard to the core stage is fixed. The behaviour of the booster has to be robust over the complete Mach number range, in order to provide sufficient safety with view to the expected aerodynamic uncertainty margins. The aerodynamic studies concerning wing shape and position are based on unstructured Euler calculations with the DLR TAU-Code 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.

The second focus of the work is the investigation of the aerodynamic interactions between Ariane 5 core stage and the LFBB’s. With view to the structural layout of wing and body, performed by MAN-Technology and Astrium, the flight condition with maximum dynamic pressure at M ≈ 1.6 is of special interest. In order to extract all aerodynamic interactions on the structural loads the isolated LFBB is compared to the Ariane 5 + 2 LFBB combination without and with junctures between rocket and LFBB. As an engineering approach this is performed by means of unstructured Euler calculations.

2. Aerodynamic Design and Analysis of the LFBB

During the LFBB design several configurations were considered. The initial LFBB-design, based on the results of [3], is the configuration “Y6“ (Fig. 2). The vehicle has a length of rref=42m, a span of b=21m and a planform area fo A ref=360m². With view to the hypersonic region of the descent trajectory, where the aerodynamic coefficients of the vehicle are dominated by the lower surface, the trapezoidal wing has an airfoil with flat lower surface. In order to allow an indifferent behaviour with acceptable flap deflections, the goal with view to the longitudinal stability is to shift the center of pressure into the region of the center of gravity, xS/l=0.62. Nevertheless, the results indicated severe problems concerning longitudinal stability and trim for configuration “Y6“. Fig. 3 shows 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, xS/l=0.75. The required flap deflections in hypersonic flow are still in the order of η=30° and more than η=-10° for M < 2. These results are obtained with very large wing- and a body flaps with simultaneous deflection (Fig. 2). Additionally the configuration is highly
unstable (Fig. 3). Based on these results it is decided to investigate LFBB configurations with canards. During the design cycle of the canard configuration a large number of wing planforms and canards is investigated. The numerical results for all the configurations are obtained with the surface inclination method HOTSOSE [4]. For the subsonic part of the decent trajectory handbook methods like [5] are applied. They allow to avoid the time consuming and complex grid generation process of Euler or Panel methods.

Planform views of the initial (“C60”) and the final configuration (“Y7”) of this study are given in Fig. 4. All investigated LFBB variants have canards with unswep trailing edges and 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 $\alpha=15^\circ$. Even for bursted vortices in the trailing edge region the maximum lift of the canards is not expected for $\alpha<25^\circ$. The strategy for the application of the control surfaces is to consider a clean wing, a body flap with constant deflection and variable canard deflection for trim. In order to allow a direct comparison to the LFBB without canard (“Y6”) the initial canard configuration “C60” has an unchanged planform area of $A_{ref}=360m^2$. Therefore, also the wing load is constant. The final configuration “Y7” has a slightly reduced planform area of ($A_{ref}=350m^2$) obtained by minor changes of canard and wing size. This is required because the masses of wing and canard have to be reduced [6]. The body itself has to be kept unchanged due to the tight margins concerning the connection with the Ariane 5 core stage.

The most important trim results are summarised in Fig. 5. It turns out that the configurations „C60“ and „Y7“ are very robust even for a realistic position of center of gravity at $x_g/l=0.62$. The obtained canard deflections are always smaller than $\eta=5^\circ$. The configuration is stable for $M > 5.5$ and only slightly unstable for $2 < M < 5.5$. Furthermore, estimations from handbook methods indicate that the required canard deflections for subsonic conditions are always smaller than $\eta=10^\circ$. An additional assessment of configuration “Y7” with a deflected body flap ($\eta_{BF}=5^\circ$) again reduces the flap deflections and results in a slightly increased longitudinal stability. Using these results configuration “Y7” is chosen as final LFBB for this design cycle. Additionally, a wind tunnel model of this configuration is projected (Fig. 6). This model is going to be used for force measurements in the DLR wind tunnels TMK and H2K. The measurements will cover the Mach number range $0.5 < M < 7.5$, angles of attack of $5^\circ < \alpha < 35^\circ$ for conditions without and with sideslip. The measurements are planned for the end of 2002. The results are going to be used to validate the aerodynamic approach and to obtain a trimmed dataset for longitudinal as well as sideslip flow. During the experiments, three canard deflections, three body flap deflections, two possible elevator arrangements and the effect of a vertical nose-fin on the lateral behaviour are going to be investigated. With view to an assessment of future LFBB versions, the canards and the wing are interchangeable (Fig. 6).

For the analysis of configuration “Y7“ in subsonic, transonic and supersonic flow, Euler grids around the configuration with a fixed body flap deflection of $\eta_{BF}=5^\circ$ are generated for canard deflections of $\eta=0^\circ$ and $\eta=10^\circ$ (Fig. 7). In order to be able to simulate the influence of the leading edge vortices on the canard efficiency, also based on Euler calculations, the original NACA 0008 was slightly sharpened along the leading edge. This approach of course does not allow to obtain the real vortex structure, but it gives a good approximation of the vortex strength and it also enables to predict a possible vortex bursting. The goal is to interpolate a trimmed aerodynamic dataset for the Mach number range $0.27 < M < 2.0$. The basis for this dataset are calculations for 15 Mach numbers, two canard deflections and four angles of attack for each $(Ma, \eta_{can})$ combination (Fig. 8). Due to the relatively unproblematic grid generation, the Euler calculations only required three weeks on a NEC SX5. For the trim calculations and the definition of the final aerodynamic dataset the lift and pitching moment coefficients are obtained by linear interpolation. For the interpolation of the pressure drag coefficients, quadratic polars are fitted into the Euler results. The skin friction drag is estimated based on the assumption of a turbulent flat plat as $C_{D_{fr}} = \frac{c_{f, wet}}{A_{ref}}$ [7]. The trim results of this approach are summarised in Fig. 9. A first comparison with the HOTSOSE results for $M > 2$ shows a good agreement of both codes for $M=2$. The obtained angles of attack are nearly identical and the canard deflections show an uncertainty of $\eta=1^\circ$. Due to the fact that the calculation of the neutral point is very sensitive concerning small changes in pitching moment, the largest differences between both codes appear during the analysis of the stability margin. The Euler results indicate a slightly unstable behaviour for $M=2$. The HOTSOSE results are more optimistic and show an indifferent behaviour and therefore, also a slightly reduced canard deflection. Due to the fact that surface inclination methods are known to be sufficiently accurate for $M > 4$, a stability margin of $\left(\frac{x_N-x_S}{l}\right)=0.02$ can be expected in the range $2 < M < 4$ (dotted line, Fig. 9).

Considering the flap deflections for subsonic and transonic flight conditions it turns out that, with the exception of $M=0.95$, all canard deflections are smaller than
\( \eta = 10^\circ \). This shows that the careful application of handbook methods for estimation of the vehicle behaviour in subsonic flow proved oneself. A comparison of the flow fields for \( M=0.7 \) and \( M=0.95 \) (Fig. 10) explains the increased canard deflections for \( 0.9 < M < 1 \). For \( M=0.7 \) a vortex is established along the leading edge of the canard. It is responsible for the relatively small canard deflections in subsonic flow because it increases the canard efficiency. For transonic conditions it is visible that vortex bursting appears at the trailing edge of the canard. This behaviour results in the situation, that the lift coefficient in transonic flow is nearly independent of the canard deflection (Fig. 8). Therefore, larger canard deflections are required.

A second interesting effect in transonic flow are the sudden tailward shift of the neutral point for \( 0.75 < M < 0.95 \) and the following frontward movement for \( 0.95 < M < 1.025 \). This behaviour may be explained with the help of Fig. 11. For the explanation it has to be recalled that the aerodynamic forces resulting from a change in angle of attack are acting in neutral point. Therefore, a comparison of the pressure distributions of two angles of attack allows an assessment of the influence of the Mach number and for angle of attack. This is visible if additionally the results for \( M=0.9 \) are considered. The comparison of \( \alpha=0^\circ \) and \( \alpha=5^\circ \) turns out that the leading edge vortex of the canard is responsible for the increase of the lift force. The vortex strength along the canard leading edge increases and this vortex also induces a low pressure region over the outer part of the main wing. If now the results for \( M=0.9 \) are considered it is visible that the overall upper surface pressure levels of the canard do not differ significantly for the shown angles of attack. Along the inner part of the leading edge the vortex strength increases with the angle of attack but in the trailing edge region vortex bursting appears. This effect partly revokes the gain in lift obtained in the inner part of the canard. Additionally, the effect of the canard vortex on the upper surface of the main wing is significantly reduced. A second important effect on the increase of lift results from the influence of the trailing edge shock on the upper surface of the wing. In subcritical transonic flow, a shock moves rearward with increasing Mach number and for angle of attack. This is visible if additionally the results for \( M=0.975 \) are considered. Here the shock already reached the trailing edge. For \( M < 0.975 \) the shift of the shock position is still possible and therefore, an increase on angle of attack results in a rearward extension of the low pressure region on the upper surface.

In summary, regarding the results for the Mach numbers \( M=0.7 \) and \( M=0.9 \), the additional lift resulting from an increased angle of attack at \( M=0.9 \) is mainly produced in the wing region and it is not dominated by the canard vortex. This explains the sudden neutral point shift to a more backward position for \( 0.7 < M < 0.9 \). For \( M=0.975 \) the same situation appears except that the shock on the upper surface of the wing already reaches the trailing edge. This effect is independent of the angle of attack and thus, the resulting lift forces acts slightly more frontward. The lack of additional suction force along the trailing edge then leads to the noseward jump of the neutral point for \( 0.9 < M < 1.025 \).

Based on the Euler results the aforesaid discussion about the neutral point position also explains the lack of longitudinal stability \((x_N-x_S)/l=0.05\) for the subsonic cruise condition (Fig. 9). This situation would lead to permanently changing canard deflections and therefore, it is to prefer to obtain a vehicle which has an indifferent or stable behaviour. The pressure distributions in Fig. 11 show that the strong interaction of the leading edge vortex and main wing are responsible for the given unstable behaviour of “Y7”. The results indicate, that the problem can be solved if the wing is defined in a way that the increase of the wing lift with angle of attack is higher than the one of the canard. Additionally, it would help to shift the center of gravity in noseward direction. For a final discussion of this problem at first the wind tunnel experiments have to be analysed concerning the existence of a vortex along the leading edge of the main wing which could increase the slope of the wing lift curve. Due to the fact that the leading edge has a large bluntness the Euler calculations are not able to predict these phenomenons.

3. Analysis of the flow field between Core-Stage and LFBB

The second focus of the paper is the investigation of the aerodynamic interactions between Ariane 5 core stage and the LFBB’s. With view to the structural layout of wing and body, especially the flight condition with maximum dynamic pressure at \( M=1.6 \) is of interest. Due to the fact that the configuration may be asymmetric for small angles of attack or for lateral flow conditions the complete configuration (Fig. 1) has to be considered as the worst case. In order to extract the aerodynamic interactions on the structural loads, the pressure distributions of the isolated LFBB and the Ariane 5 + 2 LFBB configuration without and with junctures between core stage and LFBB are compared for \( \alpha=0^\circ \) and \( \eta_{BF}=\eta_{can}=0^\circ \). As an engineering approach this is performed based on unstructured Euler calculations. These kind of calculations are sufficient for the prediction of the surface pressure distribution but of course they neglect the viscous effects. Nevertheless, they are able to show the main shock-shock-interactions which may be used for the localisation of possible hot-spots [8]. With respect to the numerical effort, even the Euler grid around the Ariane...
The LFBB’s and the core stage are connected by four connection points (Fig. 1). The fitting (frontward connection) is 25.7 m behind the nose of the core stage. An enlarged view of the fitting is given in Fig. 12. Due to the fact that the thermal loads on the fitting are very high during the reentry flight, it is protected by a pair of fairings. These fairings will be closed after the separation of the boosters. The remaining connections are at the end of the core stage, directly in front of the main engine. An enlarged view is given in Fig. 13. For the connection of core stage and the boosters six struts, each of them with a diameter of approximately $d=0.2$ m, are used. The four longer struts are in parallel and tangentially to core stage cylinder. They transmit the very strong radial forces. The two shorter struts transfer the torque into the core stage. All the struts will be assembled on the booster frame close to wing root.

As introduced before, the simulations are performed for $M=1.6$. This is the Mach number for the maximum dynamic pressure along the ascent flight. It corresponds to an altitude of 13.2 km. The overall flow field is given in Fig. 14. At the ogive nose of the core stage a detached shock is obtained. Also the two bow shocks in front of the elliptic forebodies of the boosters are visible. As shown in the enlarged view of Fig. 15 they impinge on the shell of the core stage. Reflected shocks are not obtained because the local impingement angle is nearly normal to the core stage. In the $z=0$ plane of the core stage their shock-shock-interaction induces a high pressure spot. The maximum pressure coefficients in this region are in the order $C_p=0.8$. From the structural point of view the zone between the forebody of the booster and the fitting on the core stage has to be considered very careful. In this region the shell of the core stage is very thin because it only protects the engine of the second stage of Ariane 5. Also the canards are visible (Fig. 15). For the ascent flight they are fixed at $\alpha=0^\circ$. Therefore, their effect on the pressure distribution of the core stage may be neglected. On the LFBB surface the front shock of the canards and also the trailing edge shock are visible.

In Fig. 13 the wing region is considered. The wing of the LFBB has a subsonic leading edge and does not generate a shock. But on the upper surface the supersonic region is visible. If the trailing edge is considered also the trailing edge shock may be identified on the side wall of the LFBB. In front of the fillet between circular and rectangular part of the LFBB-body detached shocks are obtained. On the LFBB surface they result in an increased pressure coefficient of up to $C_p=1.3$. The shocks also impinge on the core stage surface. The resulting shock-shock-interaction in the $z=0$ plane induces a high pressure spot ($C_p=0.7$). Also in front of the struts (rearward connection) detached shocks are obtained. They impinge on the surface of the core stage and on the lower side of the wing. On the surface of the core stage their interaction is visible directly in front of the base area. They also affect the surface pressure distribution on the lower side of the LFBB. For the symmetry plane this is shown in Fig. 16. By comparison of the isolated LFBB and the Ariane 5 + 2 LFBB configuration this figure shows the interactions between the core stage and the LFBB. The isolated LFBB has a nearly undisturbed lower surface. The pressure coefficients are in the order of $C_p=0$. The only pressure peak is caused by the shock in front of the fillet between the circular and the rectangular part of the body. The first pressure peak induced by the core stage appears at $x=7$ m. It is caused by the shock in front of the fitting (Fig. 12). Due to the existence of the core stage the strength of the shock in front of the fillet is slightly increased ($x=24$ m) and it is positioned more frontward. The third pressure peak at $x=28$ m is a result of the detached shock in front of the struts.

Resuming the comparison of the Ariane 5 +2 LFBB configuration without and with junctures to the core stage it turns out that the displacement of the struts and the fittings results in 6.8 % additional pressure drag.

4. Conclusions

The second aerodynamic design cycle of an Ariane 5 liquid fly-back booster required detailed aerodynamic datasets which allow the trim and balance of the vehicle along the complete return flight trajectory. These were obtained based on unstructured Euler calculation between $M=0.27$ and $M=2$. In the range $M>2$ surface inclination methods were applied. The complete aerodynamic dataset for a given configuration only required three weeks of working time. With view to the trim of the vehicle the results show that there is an essential need to consider a configuration with canards. The canard deflections may be limited to $\eta=8^\circ$ for subsonic flow and they are always smaller than $\eta=5^\circ$ for super- and hypersonic flow conditions. Remaining problem of the final configuration is the lack of longitudinal stability during the subsonic cruise flight. The Euler results showed that the reason for this problem is the strong interaction between the leading edge vortex of the canard...
and the upper surface of the main wing. The problem could be solved if the slope of the wing lift curve would be larger than the one of the canard. Additionally the center of gravity should be shifted in forward direction. However, a final discussion of this problem will be possible once the wind tunnel experiments for the final LFBB configurations are analysed concerning the existence of wing leading edge vortices which might increase the slope of wing lift curve.

A second focus of the work was the investigation of the aerodynamic interactions between the Ariane 5 core stage and the LFBB’s. With view to the structural layout of the wing and the body especially the flight condition with maximum dynamic pressure at \( M = 1.6 \) was of interest. As an engineering approach Euler calculations for the complete Ariane 5 + 2 LFBB configuration were performed. The results allowed a detailed analysis of the flow field. The comparison of the surface pressures between isolated LFBB and Ariane 5 + 2 LFBB configuration pointed to some regions which have to be considered in more detail during the structural layout of core stage and booster. A comparison of the configurations with and without junctures between boosters and core stage showed that the displacement of the struts and the fittings results in 6.8 % additional pressure drag.

5. References


6. Figures

Fig. 1 Ariane 5 with liquid fly-back boosters

Fig. 2 Initial configuration “Y6”
Fig. 3  Trim results for configuration “Y6”

Fig. 4  Geometry of the main canard configurations

Fig. 5  Trim results of the main canard configurations

Fig. 6  Already manufactured parts of the “Y7” wind tunnel model

Fig. 7  Surface grids of configuration “Y7”

Fig. 8  Euler lift coefficients of configuration “Y7”
Fig. 9  Trim results along the complete trajectory

Fig. 10  Flow fields around configuration “Y7”
Fig. 11  Upper surface pressure distribution of configuration “Y7”
Fig. 12 Pressure distribution in the vicinity of the fitting

Fig. 13 Pressure distribution in the vicinity of the rearward struts and the wing
Fig. 14 Flow field around the Ariane 5 + 2 LFBB configuration (M=1.6, $\alpha=0^\circ$)

Fig. 15 Pressure distribution in the vicinity of canard and LFBB forebody (M=1.6, $\alpha=0^\circ$)

Fig. 16 Surface pressure coefficients on the lower symmetrical plane of the LFBB (M=1.6, $\alpha=0^\circ$)