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Rolling Capabilities of the Experimental Vehicle ReFEx

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Abstract

The Reusable Flight Experiment (ReFEx) is an experimental vehicle under development by the German Aerospace Center (DLR). It simulates the re-entry of a reusable booster stage. After being propelled with a VSB30 rocket to an altitude of 130 km it will perform an autonomous re-entry. As the aero shape is finalized, the focus of the aerodynamic investigation turns towards more detailed analysis of occurring phenomena. The latest findings which are presented are about the steering capabilities of the rolling motion. A preliminary investigation revealed flight conditions with roll reversal. Therefore, an extensive set of viscous CFD simulations of the entire flight envelope of ReFEx (Mach numbers from $0.6 < M < 5.5$, and angles of attack from $20° < AoA < -50°$) is produced. It contains various differential canard deflections around the trim deflection. The goal is to identify flight conditions within the envelope in which the canards have nominal, reversed or very little to no roll authority. The findings have a direct influence on the trajectory which can be flown. Other investigated influences on the rolling capabilities are investigated as well and their effects on the design process is presented. The flight of the 2.72 m long ReFEx is scheduled for 2023.

Keywords: *Reusable Flight Experiment ReFEx, CFD, aerodynamic design, reusable booster*

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1. Introduction

As of late, access to space is no longer a privilege to few industrialized countries, but is part of the globalized world's technologies at a growing number of countries' disposal. This technological advancement comes with more and more competing governmental agencies and also companies in the private sector. Therefore, it has become important to not only build reliable but also cheap launch vehicles. One attempt to reduce costs of launching payload into orbit is to reuse parts of the carrier rocket, demonstrated by SpaceX's Falcon rocket. They reuse the rocket's booster stage after landing it vertically. This method requires an additional amount of fuel to steer to the landing pad and to do the parts of the deceleration. An alternative take on the landing procedure is a horizontal, airplane-like, approach. This is the basic idea of ReFEx, a flight experiment to improve technologies needed for this concept. To achieve this landing, wings and landing gear are mandatory, adding to the structural weight of the booster stage. Depending on the exact mission scenario, it is still unclear which of these two methods yields better overall performance. A combination of both might be optimal.

2. Mission Objective

The flight of ReFEx consists of three phases: The ascent, the experimental and the landing phase. First the ascent takes places. ReFEx is propelled by the ballistic spin stabilized VSB30 carrier system to a height of about 100 km and a Mach number of approx. M = 5.5. After de-spinning and separating all carrier-related parts ReFEx coasts to its apogee of approx. 130 km. Now the experimental phase begins. In this phase, ReFEx is tasked to autonomously find and follow a trajectory to reach the target destination, an ellipsoid some kilometers above ground, at a predefined speed. Reaching this target marks the start of the landing phase. Since ReFEx is not equipped with landing gear, the current plan is to perform a flair maneuver to touch ground with least possible damage to the vehicle. A model trajectory and the envelope of the experimental phase is shown in Fig 1.

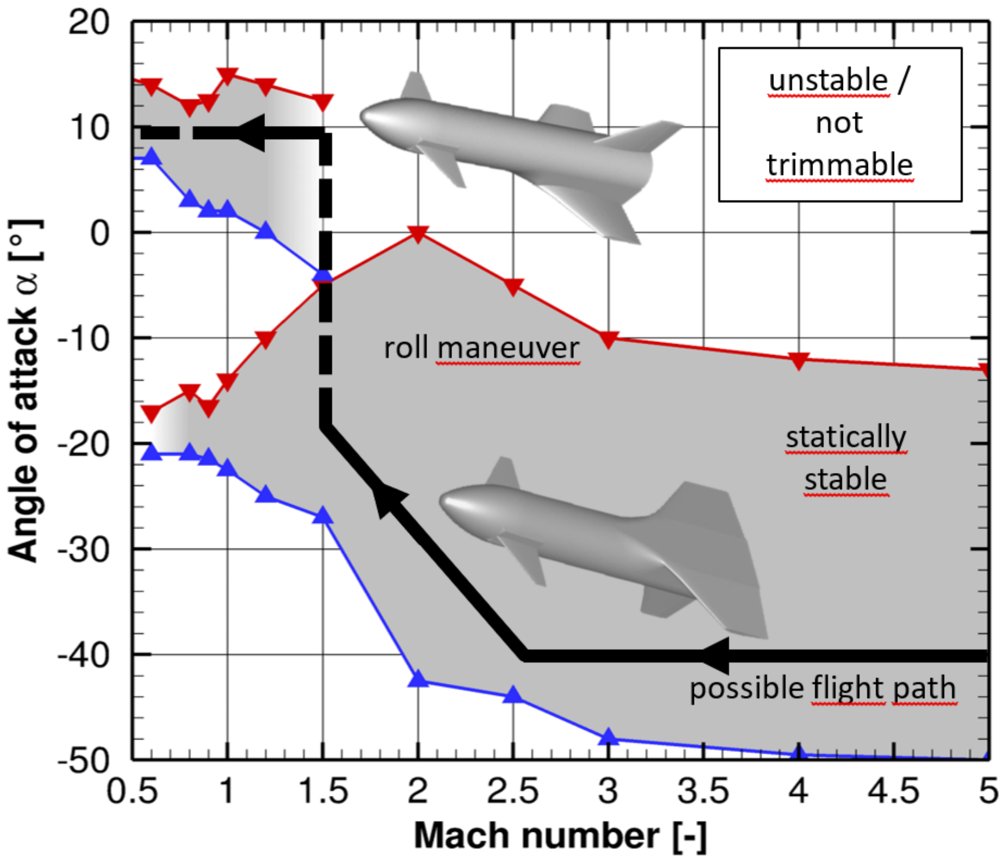

Fig 1. Area of controllable and trimmable Mach number – angle of attack (M-AoA) combinations (grey areas) and a potential flight path for the re-entry.

The main focus of the aerodynamic investigations lies on the experimental phase. It starts outside of any notable atmospheric influence. A cold gas system will orientate ReFEx into an aerodynamically stable attitude, so entering the aerodynamically dominated part of the re-entry should be problem-free. To match the needs of the trajectory, this state will be at high (negative) angles of attack. After an initial deceleration, a roll induced curve will be flown to prove maneuverability. During the entire experimental phase, the energy management is of great importance to reach the destination at the desired speed. To achieve this, a corridor of flyable pitch angles around the one preset to maintain the trajectory has to be made available. A more detailed description of the mission can be found in the overview paper [1].

3. Configuration Overview

The configuration originates from a simplified version of an older study [2] with the shared goal of designing a reusable winged booster stage but containing different requirements and constraints. This low wing configuration was designed with two canards and two angled fins. It also has a body flap, which was not used for ReFEx. That study was finished with only longitudinal investigations concerning stability being conducted (see Fig 2, left). Lateral characterization of the old configuration revealed that it was not statically stable laterally. Still, this was a good starting point to design ReFEx.

The design process was dominated by several side conditions, most prominently by the launch vehicle being a VSB30 system. They constrained dimensions, mass and aerodynamic properties of the flight experiment for the ascent phase which means:

- ReFEx had to be symmetrical because the VS30 is a ballistic missile
- Mass and dimensions needed fit within a certain range
- Side wind forces during ascent had to be sufficiently small

To fix the ascent difficulties, a fairing will be used. It will cover the asymmetrical wings and lower the side forces. Since the wings were too large to fit under a fairing, foldable wings were chosen to fix this problem. This allowed the fairing to be sufficiently slender (Fig 2, middle). A dummy fin was added at the bottom of the fairing to maintain symmetry. Furthermore, a downscaling from a 0.43 m to a 0.355 m diameter was done because of the carrier’s capabilities, resulting in a total length of 2.72 m.

The aerodynamic design process resulted in a geometry (Fig 2, right) that provides a stable and controllable corridor for the re-entry. The main difficulty was the directional stability and side slip induced high roll rates, which was solved through starting the re-entry upside down and later performing a 180-degree roll.

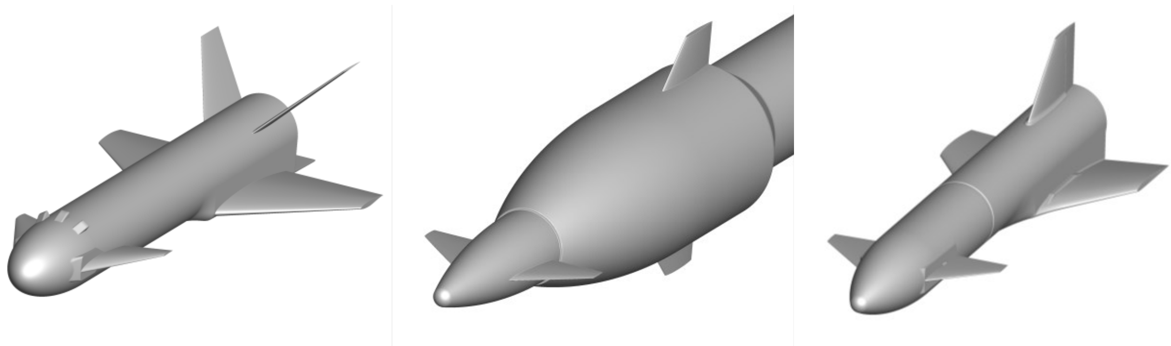

Fig 2. Representative geometries of the design process. Left: Starting Geometry. Middle: Ascent geometry with a fairing, mounted on a S30 rocket. Right: Result of the aerodynamic design.

4. Aerodynamic Characterization of ReFEx using CFD

All CDF simulations were carried out using the DLR TAU-Code [3]. The axis system used is the body fixed DIN EN ISO9300. The initial approach to do the aerodynamic characterization of ReFEx was comparable to other conceptionally similar vehicles like the Space Shuttle Orbiter or the Hopper/Phoenix RLV. The envelope is discretized for all parameters of interest. Some parameter combinations are neglected because they are unlikely to occur in the mission and the rest is simulated or measured in a wind tunnel to get the aerodynamic properties for every possible flight condition.

Initial sets created this way for ReFEx showed that the canard deflection has a greater than expected influence on the aerodynamic properties of the wings. While increasing the canard deflection angle increases its lift and induces a rolling moment, the downstream wing loses lift and a opposite rolling moment is induced. This behavior depends on the mean canard deflection as can be seen in Fig 3. The results are for different mean deflections with an additional asymmetric deflection of +3° for the left and -3° of the right canard. The rolling moment coefficient of the canards, the wings and the entire vehicle is shown. Positive values of the canard coefficient correspond with the intuitive take, that an increased AoA increases the rolling moment, leading to a positive rolling moment coefficient. At the same time, the wings show the mentioned counteracting moment. These opposing rolling moments are dominated by the canards mostly, however, there are some areas in the envelope in which the wings dominate. An example is the area in which the overall coefficient in Fig 3 has negative values. Although for the rolling motion this interaction makes controlling ReFEx more challenging, the decreased lift of the wings amplifies the pitching capabilities of the canards by around 50%.

To characterize this effect, a small sample set of simulations with a canard deflection of ±3° around the pitching moment free deflection for each M-AoA combination was created, with its main result, the rolling moment coefficient, plotted in Fig 4. Red areas correspond with the canards dominating, blue areas stand for wings domination. Since the resulting moment coefficient behavior in the blue areas is non-intuitive, they are labeled as roll reversal.

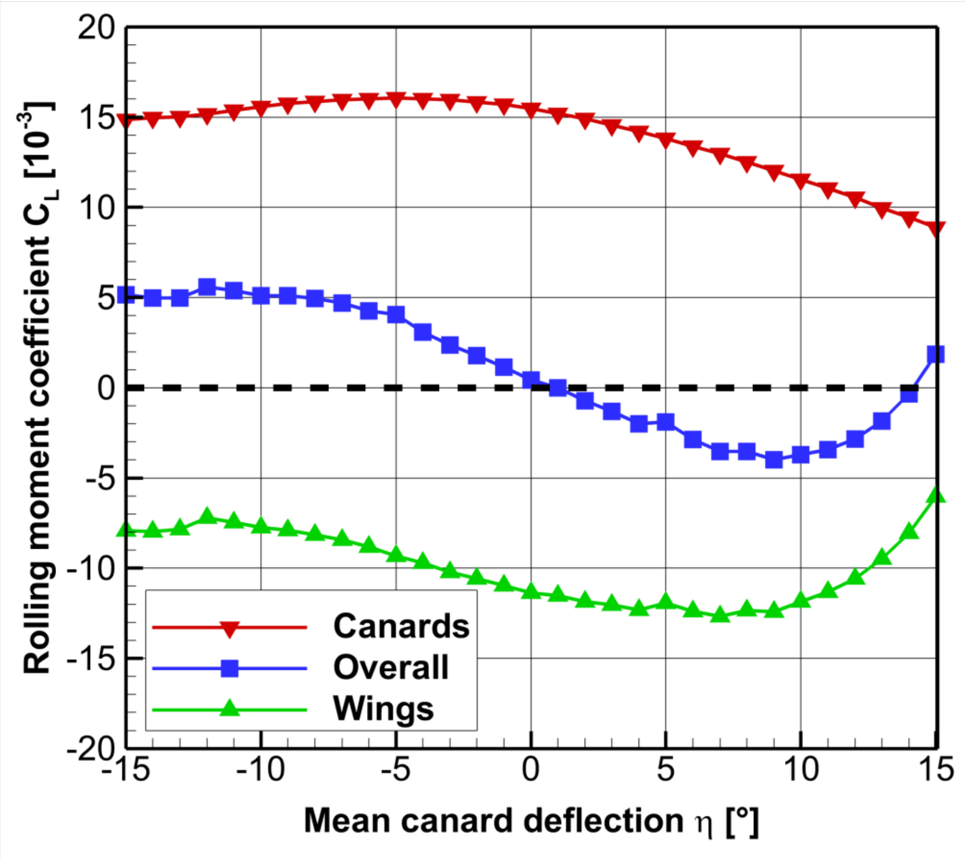

Fig 3. Roll moment coefficient for different mean canard deflections ±3° (+3° left, -3° right) at M = 1.5 and AoA = 10°. Positive values match expectation, however not only the value, but also the sign varies over the mean canard deflection.

Following through with a "traditional approach" to characterize ReFEx would lead to immense numbers of simulations, since all combinations of Mach number, angle of attack and canard deflections would need to be considered. Therefore, a different approach was necessary. The underlaying structure of the dataset is described in detail in [4]. In short, the entire envelope in Mach number and angle of attack was discretized and these flight points were first characterized for deflections that create a moment free state. Afterwards, deviations from the moment free state of several parameters like deflection angles, sideslip angles or atmospheric density were characterized to obtain the respective behavior. This method was chosen, because the canard deflection angle has a relevant impact on several other parameter's behavior. Setting the moment free state as a baseline instead of any fixed value saved the necessity to simulate the combination all canard deflections with all relevant parameter deviations. In the end for ReFEx the amount on simulations could be reduced by more than 60% [4].

To keep the amount of required meshes for this type of characterization reasonable, a method to change flap deflections is mandatory, since every investigated M-AoA combination has differently deflected surfaces. For ReFEx, a mesh-in-mesh method was used, that allows subnets to be translated or rotated freely, as long as geometric and overlap requirements are fulfilled. Still, for the wide velocity and angle of attack range several meshes were used to yield accurate results. Contrary to initial datasets, the entire envelope was characterized with viscous simulations, since the effect of the wake of the canards was not accurate for inviscid simulations. A comparison of the simulation results to wind tunnel experiments was carried out in [5].

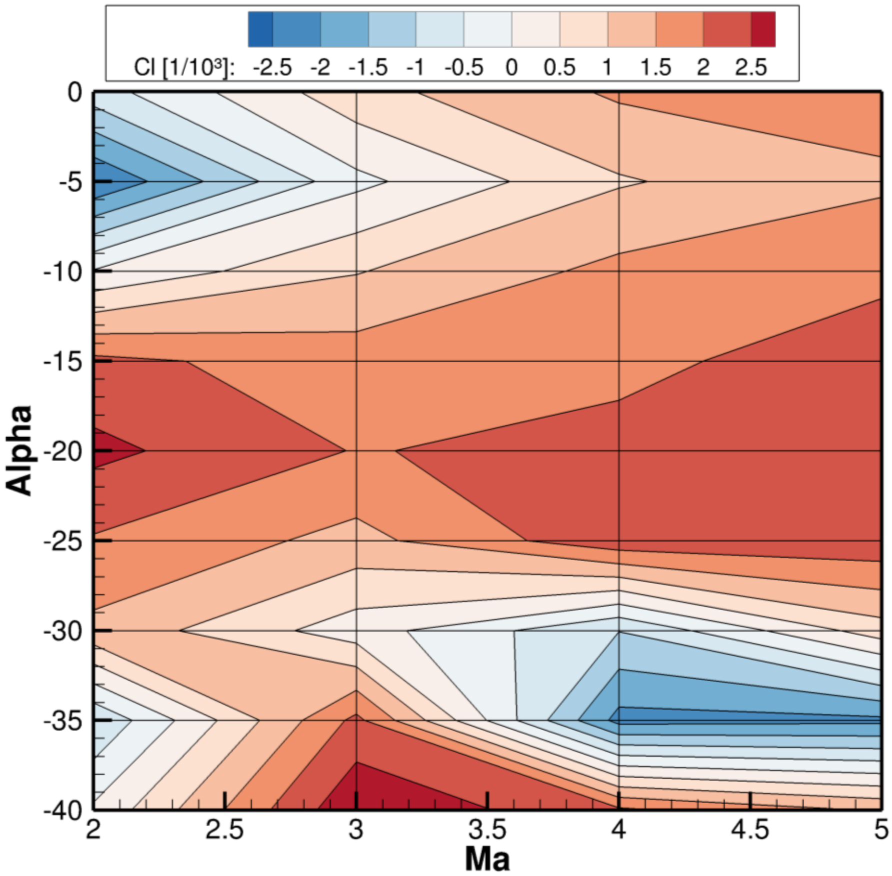

Fig 4. Preliminary characterization of the roll authority of asymmetric canard deflection. Positive values (red) represent nominal roll behaviour, whereas negative values (blue) correspond with roll reversal. In white areas, canards have no or little roll authority.

The resulting dataset contains several simulated subsets of each M-AoA combination. One is the reference set, containing the aerodynamic data for the moment free state, and for each parameter variation, another subset is added. This also makes working with the set very comfortable, since to get an overview how one parameter behaves over the entire envelope, the difference of aerodynamic coefficients of the respective subset and the reference set can be easily obtained and plotted as iso surface. This type of plots is mostly used for the following investigation of the rolling capabilities of ReFEx. A first result however is the final envelope of ReFEx with the respective canard deflection to ensure zero moments, shown in Fig 5. For simplification, this deflection is called trim deflection in the scope of this investigation. Compared to the earlier presented, preliminary envelope there are three main changes. First, the area around the roll maneuver ($1.2 < M < 1.7$) is properly characterized with data points. Second, the potential flight path at $M < 1.2$ at negative angles of attack is scratched, because no sufficient attitude control is possible in that area due to flow separation at the canards. Third, at $M > 2$, the necessary absolute angle of attack was increased, because flying AoAs closer to zero leads to trajectories with excessive thermal load spikes.

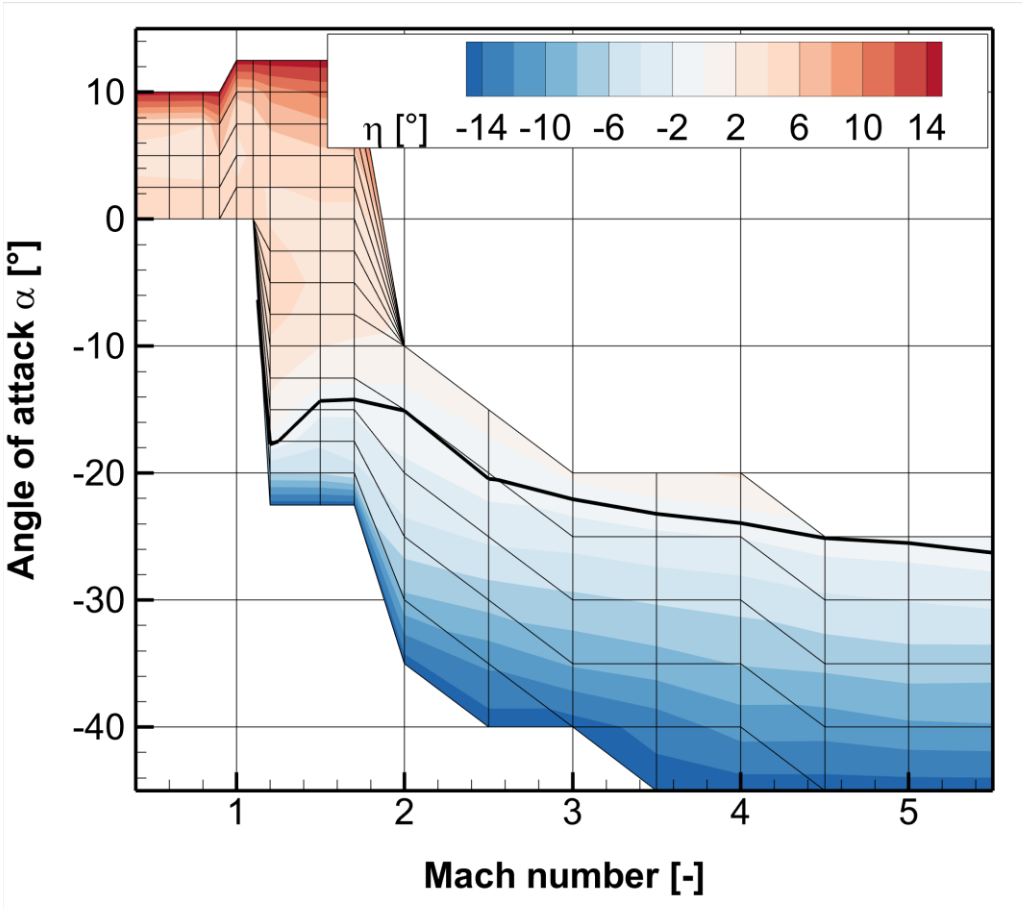

Fig 5. Trim deflection of the canards (η) of the envelope of ReFEx. The shown mesh represents the M-AoA combinations if the data set. The zero line is bold. Data points are added in the roll manoeuvre region.

5. Rolling behavior of ReFEx

To set a baseline to investigate the rolling behavior of ReFEx, a completed version of the preliminary plot of Fig 4 is created. As mentioned, for each of the over 100 M-AoA combinations, the respective moment-free canard deflection is set. Then around this deflection, an asymmetrical deflection of ±3° is added. To evaluate the resulting rolling movement of ReFEx following this deflection, the rolling moment coefficient C_L is plotted in Fig 6.

From an attitude control perspective, having no roll authority is problematic. However, ReFEx also has a rudder to create rolling moment. Both, canards and the rudder generate yawing moment at the same time. To cope with this coupling, canards and rudder are all deflected together to achieve the desired moments. Still, the position of the roll-reverse effect needs to be known precisely, because of the massive reversal area in the roll maneuver area which cannot be avoided. Therefore, this behavior must be characterized accurately, so ReFEx can be steered through these critical areas. As Fig 3 indicates, the resulting rolling moment of an asymmetric canard deflection depends on the mean deflection. However, Fig 6 only delivers the rolling moment for the respective mean trim deflection. As ReFEx will only deviate from a moment free state to compensate atmospheric disturbances, its expected state is the trimmed one or at least close to it. But there is an investigated influence on this trimmed state: thermal bending.

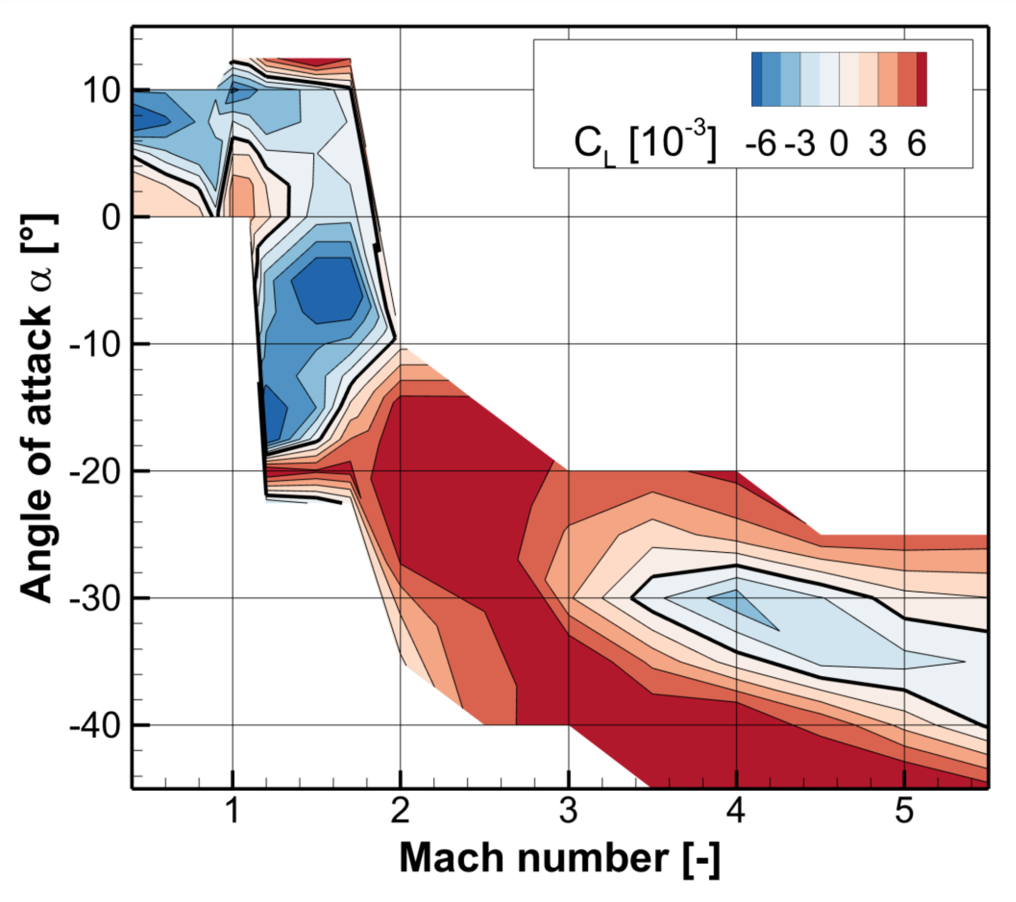

Fig 6. Rolling moment coefficient for an asymmetrical canard deflection of ±3° around the canard trim deflection. The zero line is bold. Red (positive values) areas represent intuitive behaviour while blue (negative values) represent areas with roll reversal.

As ReFEx enters the atmosphere at high negative angles of attack, its windward side (in Fig 2 the upper side) receives quite significant heat loads. A temperature difference of the upper and lower side builds up, leading to thermal bending, which in the end changes the trim deflection of the canards. This investigation was carried out in a lose coupling of CDF heat flux calculations and FE analysis for multiple points along a model trajectory. This resulted in a certain bending for each investigated Mach number. This bend is imprinted to the CFD mesh to calculate its changed aerodynamic properties, leading to changed trim deflection of the canards. The change is depicted in Fig 7, left. Mostly the effect is around 4°, with areas of lower canard efficiency containing higher values. This effect changes the areas of roll reversal. The changed zero line of the bent geometry is shown in Fig 7, right as dashed line. Especially in the roll reversal region in the higher Mach number regime, the position changes significantly. At the same time, in the rolling maneuver region there are no larger shifts. Assuming there are uncertainties to CDF data, areas with a large shift of the line should be avoided. This phenomenon is part of an ongoing study.

To further widen the range of precisely characterized mean deflection, one additional subset was simulated: mean deflection of thermal bending compensated trim deflection +3° with an additional ±3° asymmetric deflection.

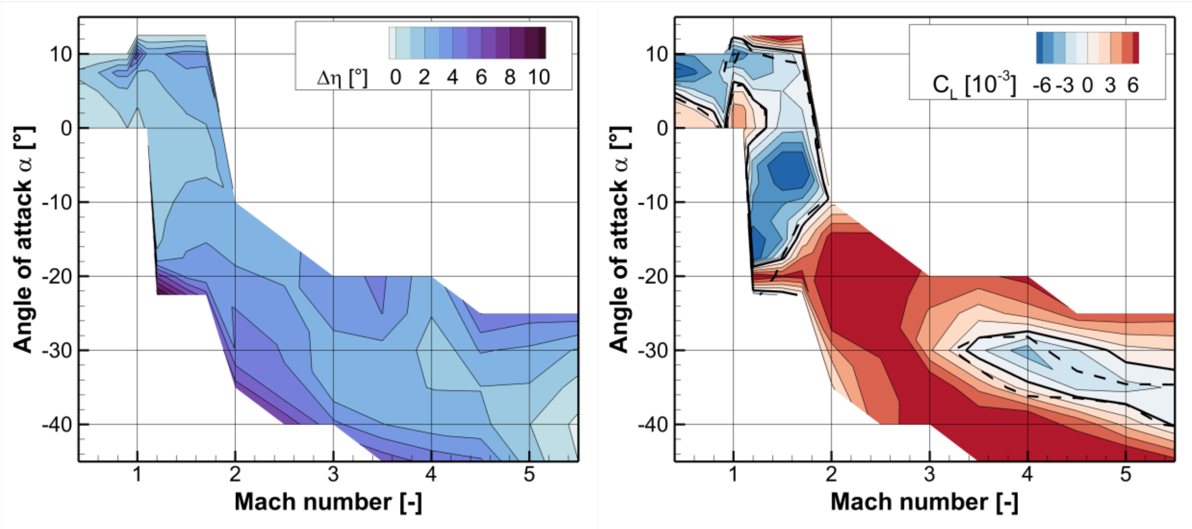

Fig 7. Effects of thermal bending on the aerodynamic characteristics of ReFEx. Left: Change of the canard trim deflection to compensate thermal bending. Right: Rolling moment coefficient of asymmetric canard deflection. Dashed line represents zero line for thermally bent geometry.

To complete the major influences on the rolling behavior, data for side slip angles as well as rudder deflections are presented. In Fig 8 the rolling moment coefficient resulting from a rudder deflection is

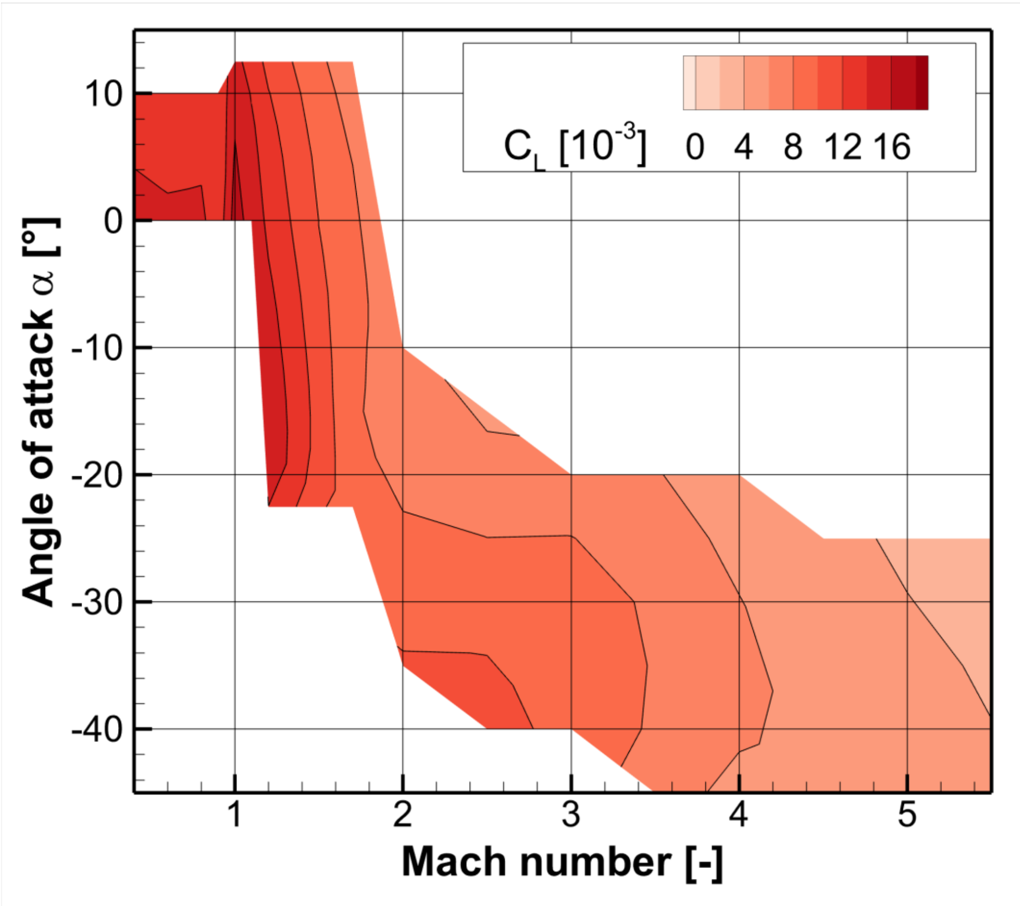

Fig 8. Rolling moment coefficient for a rudder deflection of 5°. There is no significant loss if efficiency for positive angles of attack.

shown. For the entire envelope the rudder will produce rolling moment without areas with significant loss of efficiency. As this result is not surprising for small and negative angles of attack, because there are no parts of the geometry shielding the rudder from the inflow. For positive angles of attack however, this is an important result. During the aerodynamic design process [6,7], one limiting property was directional stability. For higher positive angles of attack, fin and rudder are shielded by the fuselage, dramatically reducing their effect. This ultimately led to the belly-up re-entry trajectory.

In Fig 9 the effect on C_L of a side slip angle of 1° is shown. Its relatively small values indicate different effects counteracting each other. The two main parts of the vehicle in this respect are the wings and the fin. The wings are positioned below the center of mass, so any side force generated by a positive side slip angle should lead to a positive rolling moment coefficient component. The fin however is positioned above, creating a negative component. These partial C_L coefficients are depicted in Fig 10. This cancellation was vital in the design process [6] to ensure sufficient controllability through temporary higher side slip angles induced by side winds.

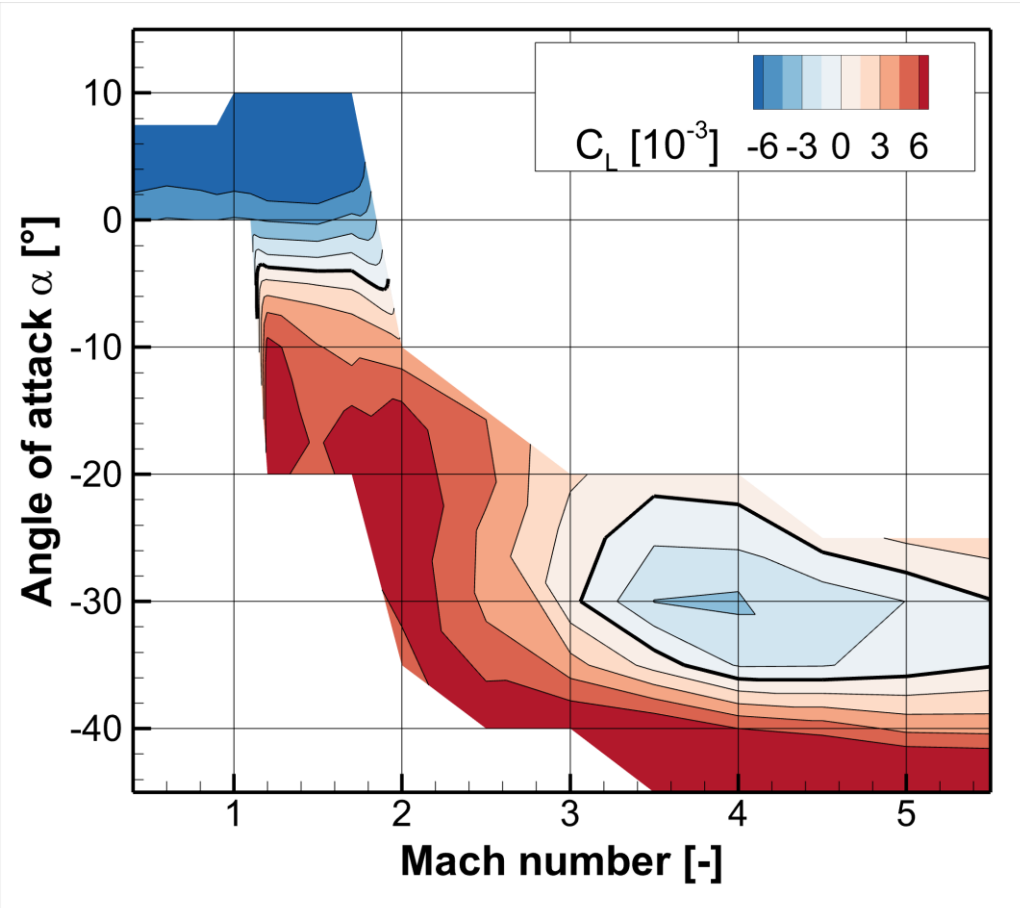

Fig 9. Rolling moment coefficient for a side slip angle of 1°. Small values indicate counteracting effects of geometry components.

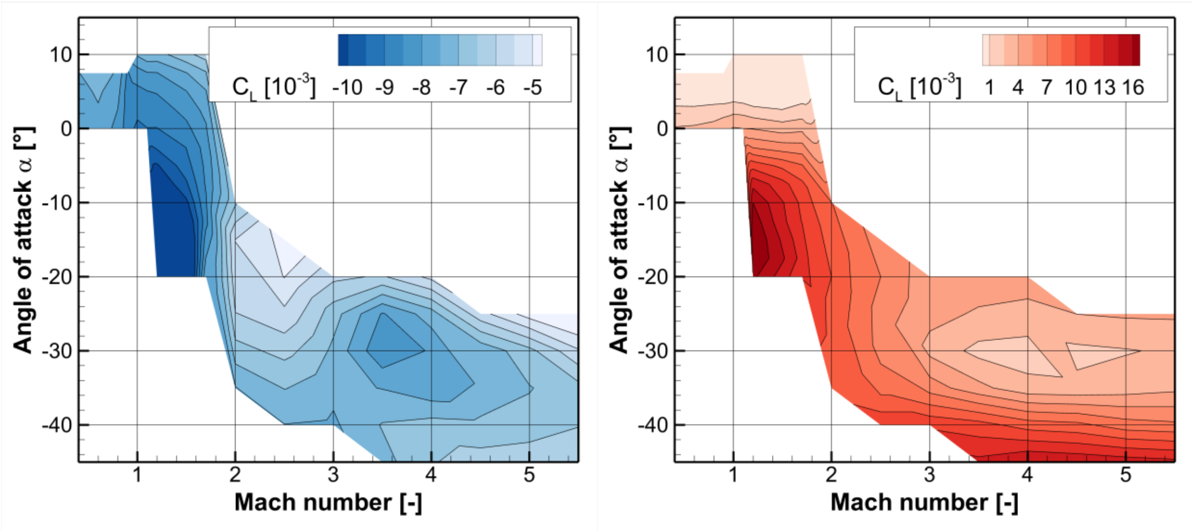

Fig 10. Opposing partial rolling moment coefficients for a side slip angle of 1°. One design goal is to have both cancel each other out. Left: Component of the fin and rudder. Right: Component of the wings.

6. Conclusion

The rolling motion of ReFEx evolved to be a driving force of the aerodynamic design of ReFEx. Its investigation overall was the most time consuming. It led not only to discard an otherwise fine belly-down geometrie, but ultimately enforced the chosen belly-up re-entry approach.

This work shows the difficulty of the aerodynamic characterization of a canard dominated flow and the found solution for this problem, which is a new type of aerodynamic data set based on trimmed deflections.

The effects of asymmetric canard deflection, thermal bending, rudder deflection and a side slip angles on the rolling motion of ReFEx are showcased. Hereby, the asymmetric canard deflection is the driver for the new data set type. Thermal bending mainly changes the pitching moment, leading to a different canard deflection necessary to reach the moment free state. This slightly changes the roll reversal positions of asymmetric canard deflections in the envelope. The rudder fulfills its purpose in creating sufficient steering forces over the entire envelope. Last but not least, rolling coefficient effects induced through side slip angles are sufficiently low over the entire envelope due to counteracting components of ReFEx.

This study concludes the aerodynamic design of ReFEx, as all design goals are now fulfilled. Further pre-flight studies are planned for the aerothermal heating and thermal bending.

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