6th International Symposium on Launcher Technology 2005, B1.4

Simulation of Dynamic Control Environments of the In-Air-Capturing Mechanism

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A few years ago, a new, innovative approach for the return of non-SSTO reusable space transportation vehicles has been proposed by DLR: The winged stages are to be caught in the air and towed back to their launch site without any necessity of an own propulsion system. This patented procedure is called *in-air-capturing*. The performance gain by this advanced method shows a possible increase in delivered payload between 15 % and 25% or allows for significantly reducing the size of a reusable system without any loss in payload mass.

The paper gives a brief description of the proposed in-air-capturing method based on latest numerical simulations data. A newly designed capturing mechanism is described and some results of a static stress analysis are presented. The preliminarily sized parts of this mechanism are used for a simplified simulation of the dynamic shock reactions. Suitable homologous models with a limited number of discrete elements are implemented in a dynamic system simulation tool taking into account the separate component masses, the spring stiffnesses and the damping coefficients. The dynamic environment is analyzed for two load cases and potential design improvements are discussed.

Nomenclature

D	Drag	N
H	altitude	m
M	Mach-number	-
S	distance	m
T	Thrust	N
V	velocity	m/s
W	weight	N
n	load factor	-
q	dynamic pressure	Pa
α	angle of attack	-
γ	flight path angle	-
η	geometrical angle	-
σ	bank angle	-

Subscripts, Abbreviations

3 DOF	three degrees of freedom
ACCD	aerodynamically controlled capturing device
CAD	computer aided design
GLOW	Gross Lift-Off Weight
GTO	Geostationary Transfer Orbit
LFBB	Liquid Fly-Back Booster
LH2	Liquid hydrogen
LOX	Liquid oxygen
MECO	Main Engine Cut Off
RLV	Reusable Launch Vehicle
RP-1	Rocket Propellant (kerosene)
SSTO	Single Stage to Orbit
UAV	Unmanned Aerial Vehicle
sep	separation

1 INTRODUCTION

A few years ago, a new, innovative approach for the return of RLV vehicles has been proposed by DLR ([1], [2]): The winged reusable stages are to be caught in the air and towed back to their launch site without any necessity of an own propulsion system. This patented procedure [3] which is currently under detailed theoretical investigations, is called in-air-capturing.

The motivation for this new approach can be traced back to a fundamental problem in the introduction of multiple stage reusable space transportation systems: Finding an adequate method for the stages' return to the launch site. A simple glide-back is only achievable with either once-around-earth vehicles (very high Δ-v requirement close to SSTO) or small booster stages (only small increment to launcher's total Δ-v). In any other case secondary landing sites have to be selected or precautionary measures for a powered return flight are to be included in the reusable stage. Obviously, both approaches are closely bonded to serious drawbacks.

Unfortunately for future reusable stages, today's entire launch sites are located such that only scarcely populated areas (e.g. oceans) are found downrange. This is obviously due to the fact, that any considerable damage on earth by the fall-back of expended stages or destroyed launchers has to be strictly avoided. Therefore, it is highly difficult to find existing reachable landing fields, or in case of an ocean it is even quite impossible to construct them at all. Consequently the requirement to reach an alternative landing site has a strong impact on the launcher's trajectory and hence performance. In any case, this method requires a considerable amount of additional infrastructure to ship the reusable stage back to its original launch site.

Techniques of powered return flight avoid these problems but obligate a propulsion system and its fuel, which raises the stage's inert mass. In-air-capturing offers a different, more promising approach: The winged reusable stages are to be caught in the air, and towed back to their launch site without any necessity of an own propulsion system. This so called in-air-capturing method is to be supported by large cargo transports, offering sufficient thrust capability to tow a winged launcher stage with restrained lift to drag ratio.

The following chapter 2 gives an overview on the principle functionality of in-air-capturing, demonstrates its theoretical feasibility proven in flight dynamic simulations, and quantifies the performance gain. Chapter 3 describes the capturing device and the preliminary design of its mechanism. Finally, the paper addresses the simulation of dynamic shock reactions inside the capturing device in chapter 4.

2 DESCRIPTION OF THE PROPOSED IN-AIR-CAPTURING METHOD

2.1 Principle functionality

A schematic of the reusable stage's full operational circle is shown in Figure 1. At the launcher's lift-off the capturing aircraft is waiting at a downrange rendezvous area. After its MECO the reusable stage is separated from the rest of the launch vehicle, and afterwards performs a ballistic trajectory, soon reaching denser atmospheric layers. At around 20 km altitude it decelerates to subsonic velocity and rapidly looses altitude in a gliding flight path. At this point a reusable returning stage usually has to initiate the final landing approach or has to ignite its secondary propulsion system.

Within the in-air-capturing method, the reusable stage is awaited by an adequately equipped large capturing aircraft. Both vehicles have the same heading still on different flight levels. The reusable unpowered stage is approaching the airliner from above with a higher initial velocity and a steeper flight path, actively controlled by aerodynamic braking. The time window to successfully perform the capturing process is dependent on the performed flight strategy of both vehicles, but can be extended up to about two minutes. The entire maneuver is fully subsonic in an altitude range from around 8000 m to 2000 m. The upper constraint is set by the requirement to reach full aerodynamic controllability of the winged stage. After successfully connecting both vehicles the winged reusable stage is towed by the large carrier aircraft back to the launch site. Close to the airfield, the stage is released, and autonomously glides like a sailplane to earth.

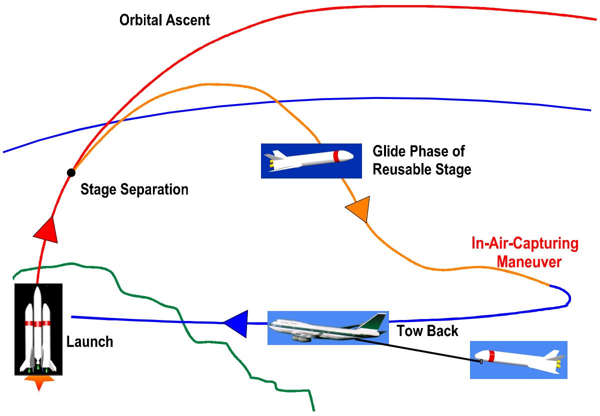

Figure 1: Schematic of the proposed in-air-capturing

As a basic requirement tracking of the returning launch vehicle is always possible by radar, or satellite, and is communicated via direct data link. Therefore, a real-time optimization of the aircraft's geographical position is manageable. Since the ballistic phase of the stage extends to several hundreds of seconds, a correction of up to 100 km is achievable, if separation-conditions unexpectedly differ notably form the nominal case.

2.2 Simulation of the RLV approach to the capturing aircraft

The mathematical model used for the simulation of the capturing procedure includes a complete set of nonlinear dynamic equations of motion in three-dimensional space for both vehicles (the winged reusable stage and the capturing aircraft) with atmospheric simulation and a mathematical model of the winged stage's control system. A description of the control algorithms can be found in references [1] and [2].

After deceleration to subsonic speed at an altitude around 20 km, the winged stage is actively heading towards the capturing aircraft. Under nominal circumstances the latter is assumed to be in a 'passive' mode, just cruising at constant altitude (e.g. 8000 m) and relatively low flight Mach-number of about 0.55 (400 km/h). It has to be assumed that both vehicles are now permanently in communication with each other.

During descent the reusable stage is able to perform some position-correction maneuvers and to dissipate kinetic energy, if required. It plays the 'active' part in the approaching maneuver. After penetrating the denser atmospheric layers, the winged stage can be aerodynamically controlled by the angle of attack α, the trajectory bank-angle σ, and the air-brake deflection angle δ_{FB}.

The realization of the control law described in [1], [2].results in a precise heading of the reusable stage in the direction of the capturing aircraft, and is maintained until capturing. The winged stage firstly glides with a very steep angle (e.g. around -18°) and reduces gradually its velocity, while the capturing aircraft flies in the flight level $H \approx 8$ km with the constant velocity. When the returning launcher's position relative to the aircraft comes to a certain vector point, the end phase of the approaching maneuver is initiated. Then the aircraft itself starts a descending glide path, still in front of the stage. In the standard simulation a descent gliding of both vehicles is chosen, with a flight path angle γ_{capt} achievable for an L/D ratio slightly below the winged stage's maximum. The more or less parallel descending of both vehicles enables a smoother approach maneuver, and an extension of the duration available for the capturing. It further makes it possible to correct the distance between both vehicles and to adapt the flight velocity of the winged stage by air-braking very precisely. But the almost collinear flight requires that the normally higher lift/drag ratio of the capturing aircraft (about 15...16) has to be adapted to the L/D of the reusable winged stage (around 4...6). This can be achieved by using air-stream spoilers, an air brake, and /or by lowering the landing gear to increase drag. Similar maneuvers are carried out by Gulfstream II jets operated as Space Shuttle training aircraft [5].

An approach maneuver for a reusable stage with separation velocity around 2 km/s is described in [1], [2]. One example of the aerodynamically controlled approach is shown in Figure 2 displaying the altitude profile of both vehicles flying in parallel.

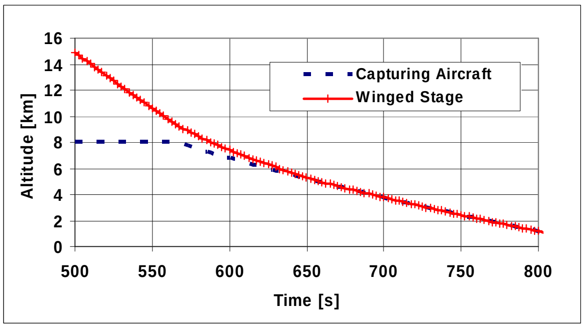

Figure 2: Simulation of the reusable stage's final approach procedure to the capturing aircraft starting 500s after separation from launcher

As can be seen from Figure 3, the total distance between the two flying craft falls short 0.5 km around 655 s after separation. Subsequently the distance could be controlled in this simulation at a minimum range between 155 and 200 m for duration of 130 s. The upper boundary is not set by vehicle control, but by a minimum acceptable level above ground. The final altitude in this simulation is as low as 1.2 km. A time for capturing up to at least one minute is nevertheless well within reach, since the altitude after this period still accounts for more than 2.8 km.

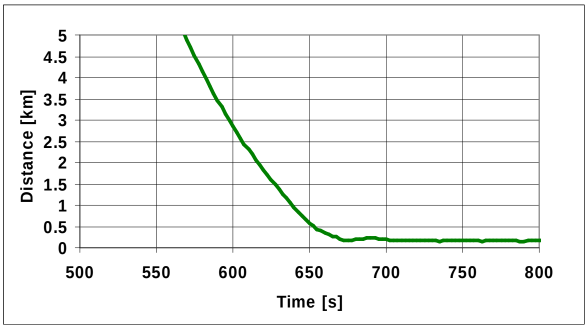

Figure 3: Total distance between the two stages in final approach procedure starting 500s after separation from launcher

Analyses of off-design operation show that the flight dynamic potential of the descending vehicle to dissipate energy is quite comfortable. Even if separation time varies about more than one second, the stage should be able to reach its regularly foreseen rendezvous area, while staying within the loads envelope [1], [2]. Since the capturing aircraft has an own capability to improve its geographical position, further margins exist.

2.3 Performance Gain by the in-Air-Capturing method

The interest in the advanced capturing method can best be demonstrated by its possible performance gain. The basic assumptions of the detailed calculations are described in [1], [2].

The first quantified assessment of the advantage is performed for a reusable first or booster stage with a separation velocity around 2 km/s. The reference booster is a LOX-RP1 powered winged stage using kerosene fuel for the fly-back mission. A heavy lift launch into GTO is regarded. Three sub-variants of the in-air-captured stage are considered (A, B, C – see [1], [2] for detailed description), all derived from the original JP-powered fly-back configuration (reference).

The resulting payload performance is increased by around 15 % for the in-air-capturing variants A and B with lower MECO mass as shown in Figure 4. Case C reaches by definition the same payload mass as the reference configuration because this variant aims for a maximum reduction in the size of the reusable booster without loosing payload capacity.

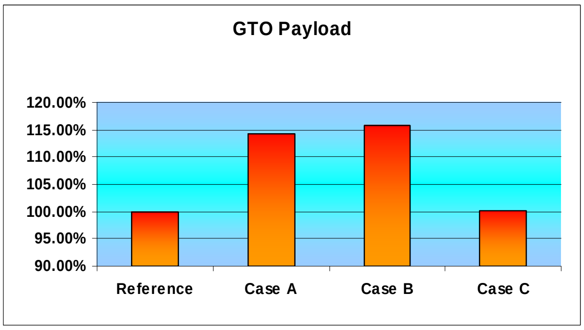

Figure 4: Comparison of GTO payload of different to be captured stage concepts (A through C) with conventional jet powered fly-back stage (reference)

If the size of the RLV is considerably reduced, holding the payload constant, at least 17 % diminishing of mass is achievable (Case C) in a still conservative assumption. (see Figure 5)

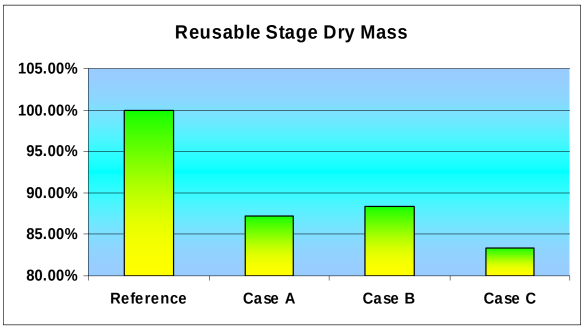

Figure 5: Comparison of RLV dry masses of different to be captured stage concepts (A through C) with conventional jet powered fly-back stage (reference)

It is evident that in case of a fly-back stage with considerably higher separation velocity, the payload-gain by introduction of the in-air-capturing method is further augmented. Recently, an RLV concept called Reusable First Stage (RFS) became quite popular in European discussions about options on a next generation launcher [6]. RFS should have a high separation velocity (approximately Mach 13) to reduce the size and hence costs of an expendable upper stage. However, the required fuel for fly-back rapidly grows beyond any reasonable amount. The in-air-capturing method might be the only promising way for an RFS to ever become reality.

Even in the case launch vehicles are not designed to perform a direct fly-back to the launch site, in-air-capturing offers significant advantages. If possible, these concepts try to avoid any secondary propulsion system and try to reach a downrange landing site. Although, on a first look it might seem that in-air-capturing is not of primary interest for these RLVs, it can be demonstrated that considerable quantified performance advantages exist [1]. Moreover, in-air-capturing offers the opportunity to directly return the reusable stage to its launch site, reducing operational expenses and turn-around time.

3 DEFININITION OF A CAPTURING DEVICE AND PRELIMINARY DESIGN OF ITS MECHANISM

3.1 Selection of a capturing device and capturing procedure

The capturing technique itself has been systematically investigated in 3 DOF simulations (see [7], [2]). The process and the necessary mechanics are by far not optimized yet, but preliminary analyses give an indication of the most promising technique. Four different types of capturing methods have been studied:

- The first procedure, already early proposed in [1], is the harpoon principle with a missile launched from the capturing aircraft and directly shot versa the returning stage,
- a variant requires for the missile to perform a loop maneuver, and approach the RLV from behind to considerably reduce the impact loads. This second capturing option had to be dropped because of impractically large rope length (see [7], [2]).
- The third option fires the missile from the reusable stage versa the capturing aircraft, also decreasing relative velocity and hence loads.
- The last alternative employs an aerodynamically controlled capturing device (ACCD), which is to be released by the airplane and then towed, cautiously approaching the launcher.

The first three capturing types employ an air-to-air missile capable of achieving rapidly a connection but in a first step only by a small pilot rope. After successfully connecting the two vehicles, the actual towing rope has to be drawn out.

The fourth alternative employs a different approach with the aerodynamically controlled capturing device (ACCD), which is to be released and then towed by the airplane. This device (a preliminary artist impression is shown in Figure 6) contains the connecting mechanism and simply advances the stage by its own drag and lift, provided by small wings (span 1.6 m). Actuators control the ACCD’s orientation and the approaching velocity might be further controlled by braking of the towing rope from inside the aircraft. With a release initiated at 230 m distance between the two crafts, the whole maneuver takes about 14 s in the nominal case. All loads remain below 3 g and the final relative velocity is at 5 m/s [7]. It has to be noted that although the time to achieve capturing is longer than those with missile fired harpoons, full connection by a towing rope can already be achieved at the very moment of capturing. Therefore, the total time required for the in-air-capturing is the shortest with less than 20 s (see [2]).

Reference [2] compares the main data of the three feasible capturing options. The analyses of the capturing procedures clearly indicate that the aerodynamically controlled capturing device (ACCD) offers the largest time margin (wrt. the parallel flight duration of 120 s) as well as the lowest loads. It further offers a cost advantage compared to the expendable missiles since this device can easily be reused for each capturing. Thus, the ACCD is the baseline capturing device and a suitable mechanism has been developed for the ACCD and its respective loads.

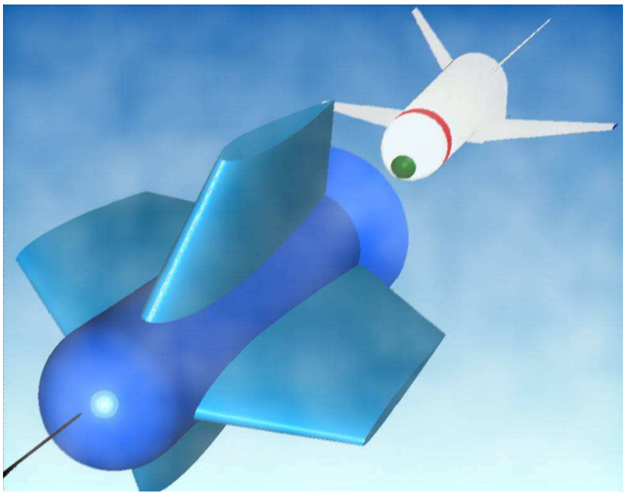

Figure 6: Rendering of the ACCD and the returning stage cautiously approaching each other

Technical requirements of the tow-aircraft are given in [2]. The rope and its mechanism have to be designed to withstand the pulling stress with regard to dynamic loads. The maximum values are most likely being reached during pull-up of the assembly after capturing. A towing rope diameter of 1.6 cm is estimated to be sufficient for up to 200 kN load [2].

The thrust requirements of the capturing aircraft are dependent on the reusable stage's mass and its L/D-ratio. The thrust reserve of the capturing aircraft has to exceed 50 to 200 kN in an adequate flight altitude [2]. A four engine jetliner without normal cargo loading offers sufficient thrust margins. This is corresponding to an Airbus A-340 or Boeing-747-class jet, which have been produced in large numbers. Moreover, a considerable quantity of these airplanes is already available at an affordable price, since some of them have been retired from commercial airline service.

A catastrophic midair collision has to be avoided by fully automatic and redundant control avionics of both vehicles operating in a synchronized mode. Any pilot interference in this maneuver from the capturing aircraft is by far too slow, to have a positive impact. Since no real demanding pilot work is foreseeable, one should seriously consider redesigning the capturing and towing aircraft as an unmanned aerial vehicle. Taking into account the significant progress recently achieved in UAV avionics, this is not such an exotic idea. By giving up pilot control for all capturing missions, it might be also possible to broaden the flight envelope, which will not be acceptable with men on board. This further enables high risk maneuvers – if ever required - which are otherwise excluded and would result in the loss of the returning stage. Hence an unmanned towing aircraft will augment overall reliability and safety of the in-air-capturing method.

3.2 Preliminary design of the ACCD capturing mechanism

The capturing mechanism is a critical part which recently has been preliminarily designed for the static load conditions encountered when capturing and towing a large fictive RLV stage. The mechanism lay-out has to be defined for correct kinematic functioning in capturing-, towing-, and release-mode, as well as for good shock attenuation.

This translates into certain design requirements for which some of the most important are:

- fully inelastic shock between ACCD and RLV stage in axial direction during capturing,
- elastic shock in radial direction of the ACCD,
- axial shock design load approximately 10 kN,
- to allow for a maximum axis deflection between ACCD and RLV of 10 degrees with automatic reorientation to the towing axis.

A preliminary design of such a capturing mechanism has been developed (see Figure 7) and has been subsequently mechanically sized supported by Finite-Element stress and deformation analyses [8].

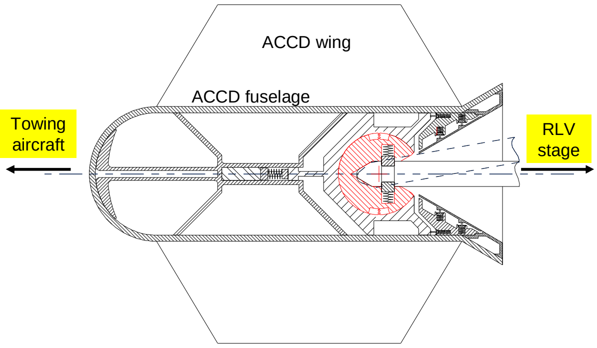

Figure 7: Sketch of the capturing mechanism inside the ACCD geometry highlighting the ball-shaped head in red and the RLV stage anchor shown in parallel and deflected position

All elements of the mechanism fit into the ACCD fuselage and consist of

- a ball-shaped head with ball jacket,
- industrial shock-absorber,
- different spring and damping elements, and
- additional support structure.

The principal idea of the mechanism is to direct a long passive anchoring device from the RLV to the capturing- and hold mechanism inside the ACCD. A funnel like opening at the ACCD’s back with a 30 deg. cone opening allows for the mechanically steered guidance in case of small flight position imperfections prior to connection and for the required axial deflection between both flying items in the capturing procedure and also thereafter in towing flight. Inside the ACCD all axial loads as well as the relative pitch and yaw movements between the different flight vehicles are transferred through a ball joint to its jacket capable of axially gliding inside the ACCD fuselage. Relatively high local pressures between the ball and the jacket will require also a good lubrication between those two metallic parts.

The connecting shock between both vehicles is transferred in the ACCD's forward direction to an industrial shock absorber (see schematic of load flux in Figure 8, top position). Such a device allows for a constant deceleration with a moderate axial force and rapid oscillation damping. The current design has to absorb about 1.9 kJ of kinetic energy and the maximum deceleration force reaches 27 kN. The ball head construction ensures that the shock damper has to absorb only the predominant axial loads. The smaller side loads will result in a ball deflection which should be countered by reset forces bringing the ball back into its nominal orientation.

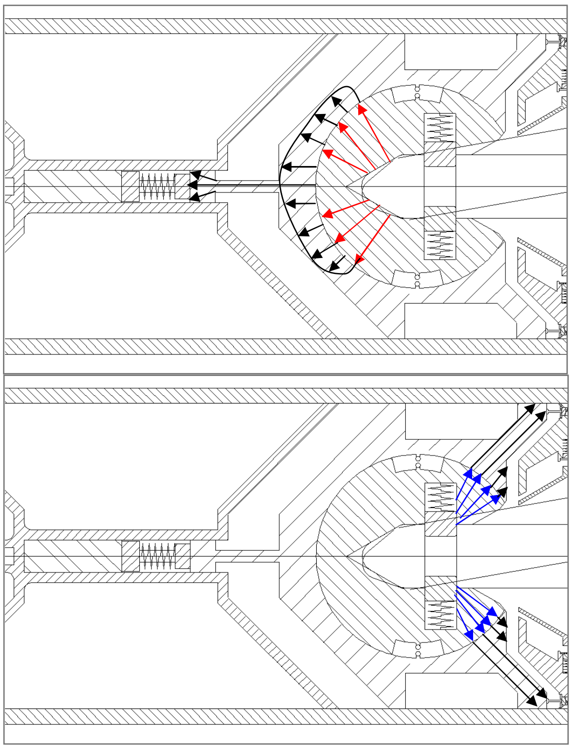

Figure 8: Schematic representation of the nominal load flux inside the mechanism (Case 1: capturing at top, Case 2: towing at bottom)

A very simple potential technical solution to create such a reset force might be realized by a compressible double torus as shown in Figure 9. This design would allow for a maximum ball deflection of 10 degrees in any direction and provide the forces (pneumatically and / or by internally embedded springs) to bring it back in the normal direction.

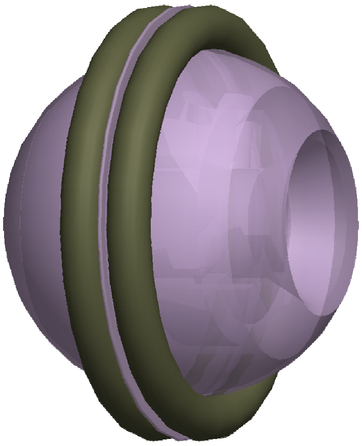

Figure 9: Double torus-like pneumatic support of the ball-shaped head providing reset forces in case of head deflection

The tautening of the towing rope after successful capturing will move the ball head with its jacket in the opposite, the ACCD's backward direction. This movement is soon to be stopped by the ring structure at the ACCD's back. A schematic of the corresponding load flux can be seen in

Figure 8 in the bottom position. The rope tautening might be a sudden event requiring also some kind of shock damping. Several technical options are investigated. In a first approach for sizing of the main elements of the mechanism, it has been assumed that several helical springs are circumferentially mounted between ball jacket and ACCD stopper ring. This assembly will have to be checked on its dynamic response in the investigations described in chapter 4 and probably will have to be adapted.

The two load cases of Figure 8 have been identified as dimensioning and are analyzed in static structural stress and strain calculations. The finite element method has been used to obtain the stresses in the complex-shaped parts. These data help in an iterative sizing of the material thickness and in a reduction of the mass. All of the parts have been separately analyzed [8] with the tool ANSYS to avoid modeling of complicated surface interfaces. Instead such interfaces are replaced by a set of distributed loads or boundary constraints delivering the respective reaction forces. Although this approach might not always fully represent the actual conditions, it is found adequate for a preliminary sizing of the components.

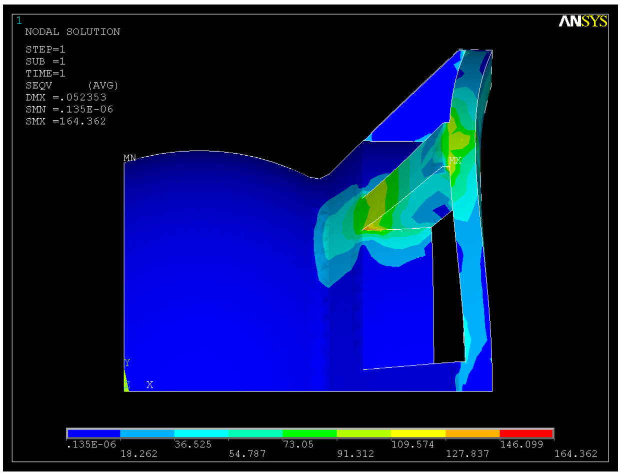

Figure 10: Von Mises stress in the head jacket structure for the towing load case [8]

Figure 10 shows an example plot of the von Mises stress in the jacket part subject to the high load towing condition. The (blown up) deformation resulting from the concentrated introduction of force by one of the spring connections is clearly visible. A large part of the material is subject to a low stress level of less than 10 MPa. The maximum stresses in Figure 10 do not exceed 165 MPa which is well below the material strength. Thus, some wall thickness reduction is still possible.

A three dimensional representation of the latest 'in-air-capturing' mechanism structure is illustrated in Figure 11. A mass balance has been established based on this solid model of the structure. The sum of the ACCD component masses is currently reaching 200 kg which is beyond the mass target of 150 kg. However, the very low stress levels found in large areas give a good potential in further reducing the component masses. The static strength feasibility of the mechanism's structure is generally proven. Thus, the data can be used as input variables for the simulation of its dynamic environment.

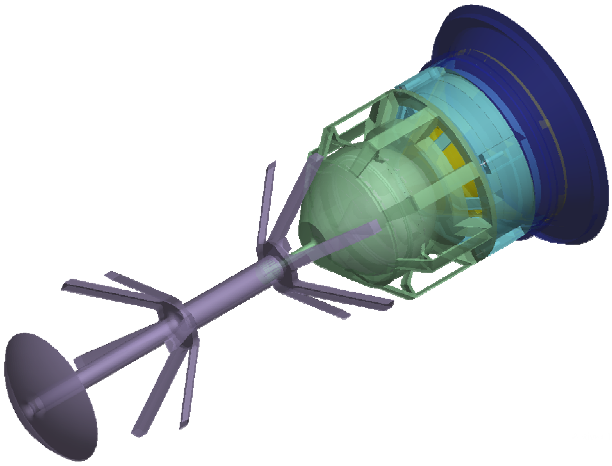

Figure 11: 3-D CAD-representation of 'in-air-capturing' mechanism to be integrated inside the ACCD fuselage

4 SIMULATION OF DYNAMIC CONTROL ENVIRONMENT

This chapter focuses on the simulation of the dynamic shock reaction for which a good knowledge is essential to effectively control the loads. Suitable homologous models are implemented in the DLR dynamic system simulation tool *RFD* taking into account the separate component masses, the spring stiffnesses and the damping coefficients. The simplifying approach of using a dynamic system simulation tool with a limited number of discrete elements is preferred over a complex FEM-model. Such a methodology allows for rapid parametric analyses of component properties selection and for the convenient assessment of potentially required design improvements.

The load cases are similar to those investigated in the static structural analyses described in section 3.2. The characteristics are preliminarily found by iteratively calculating the two load cases and adapting to all relevant conditions.

4.1 Case 1: Capturing shock between ACCD and reusable, returning stage

In a first approach the capturing shock has been simulated with the ACCD impacting the RLV stage with its final approaching velocity v_0 (4.9 m/s). Note that only the axial portion of the velocity has been considered. The suspended mass does not include ball head and jacket because both are already directly connected at this instant to the anchoring device of the stage. The homologous model as displayed in Figure 12 is very simple, however, representative of all major forces in the one dimensional case. At the initial conditions the potential energy in all spring and damping elements is zero and the remaining mass of the ACCD is moving with the velocity v_0 relative to the stage. All other outside forces acting on the system are assumed to be in equilibrium. According to the initial design, the industrial shock absorber should have been the primary damping device but also forces of the helical spring system which should reduce the tautening shock (see section 3.2) would influence the dynamics of the model. Further, the ACCD’s funnel is protected by separately suspended plates with very small damping characteristics.

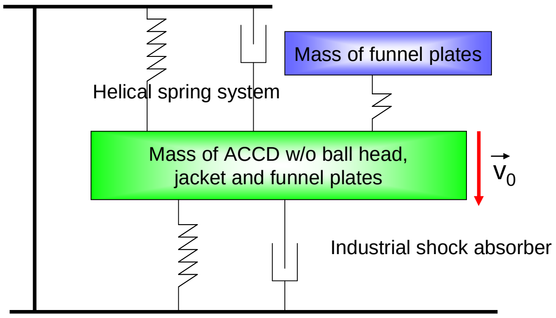

Figure 12: Homologous dynamic model of capturing shock acting on ACCD with original design of helical spring system connected

While the dynamic requirements of the industrial shock absorber have been already defined for the static analysis, all other characteristics were not fixed before starting the dynamic analyses. Figure 13 shows the acceleration, velocity, and axial position vs. the inertial system of the RLV stage prior to impact. In this test case, the industrial shock absorber reaches its intended almost constant deceleration level of -15 g (20 kN) after 5 cm of ACCD movement. At 0.05 s the deceleration is completed followed by a slower relaxation period.

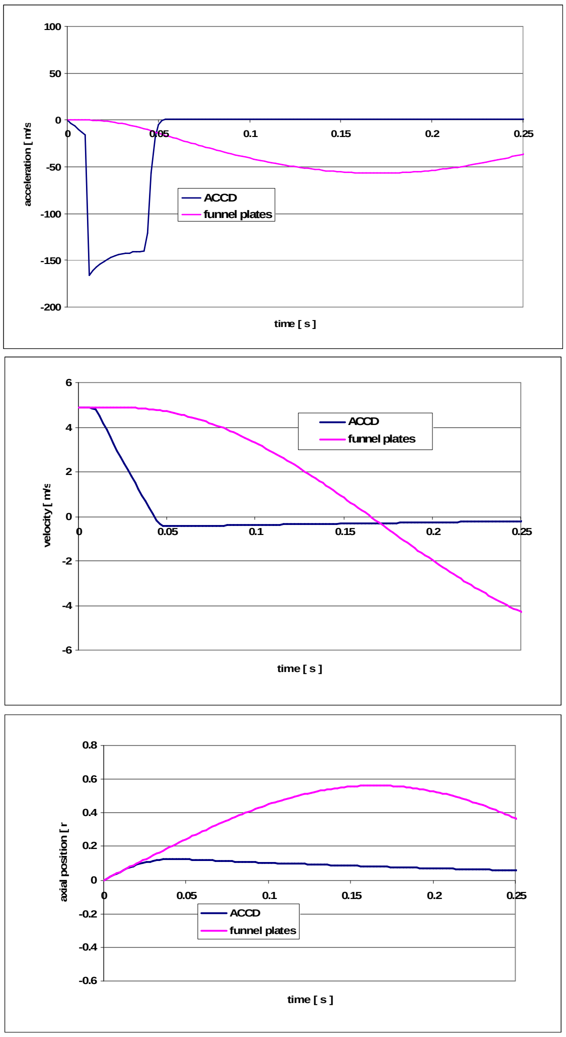

Figure 13: Dynamic reaction of capturing shock acting on ACCD in preliminary test case

The funnel plates have a smooth acceleration level in this simulation which results in a large deflection of almost 0.6 m. The latter is obviously not acceptable from a kinematic point of view. Considerably more resistant springs will be required which will dynamically influence the whole system (see section 4.3). A small influence of the helical spring system can be detected in Figure 13 before the shock absorber becomes active. These spring and damping elements support the shock absorber but have minor influence on the overall dynamics of this simulation. However, the damping requirements on the tautening spring have to be found in the dynamic simulation of load case 2 which is described in chapter 4.2.

4.2 Case 2: Tautening of the towing rope

In load case 2 a sudden tautening force is transmitted through the towing rope to the ACCD. This force is to be redirected by the ball head with its jacket to the RLV stage as shown in Figure 8, bottom position. In the original design of chapter 3.2 these loads are to be distributed by a system of four helical springs including dampers to the jacket. The suspended mass does not include ball head and jacket because both are again directly connected to the anchoring device of the stage. The elasticity of the anchor has not been included in this first analysis. Both connected masses in the homologous model displayed in Figure 14 are moving in parallel without relative velocity to each other at the start of the simulation.

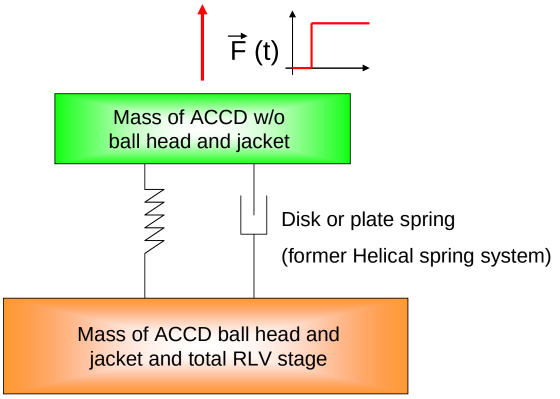

Figure 14: Homologous dynamic model of tautening shock acting on ACCD and RLV stage

As initial condition the potential energy in all spring and damping elements is zero. After 0.01 s a sudden force of 200 kN coming from the capturing aircraft via the towing rope is acting on the ACCD. In the simplified dynamic model of Figure 14 no other outside forces are assumed to be effective. In reality drag, lift and inertia in three dimensional space of the RLV stage are in equilibrium to the rope force, rapidly reducing the resulting acceleration to zero. However, for studying the ACCD’s dynamic reaction the above described simple approach seems to be adequate.

It rapidly turns out that the helical spring stiffness as assumed in the previous section 4.1 is unfeasible for the much larger tautening shock load of 200 kN because otherwise the relative motion of the ACCD vs. the RLV has to exceed its own total length. Stiffness and damping coefficients are enlarged by a factor of more than 20 and a few data of the dynamic simulation are presented in Figure 15.

While the 100 Mg RLV stage is suddenly accelerated by 200 kN to 2 m/s^2, the relative acceleration of the ACCD by the spring seems to remain at almost zero until the RLV has reached the same velocity of 0.816 m/s respective to the inertial system at the start of the simulation. However, a very short acceleration peak of about 1 ms (not visible in Figure 15) accelerates the ACCD before this rope tautening force is annihilated by the hydraulic damper. The maximum deformation of the spring system in this case is 0.166 m which might be within the acceptable range.

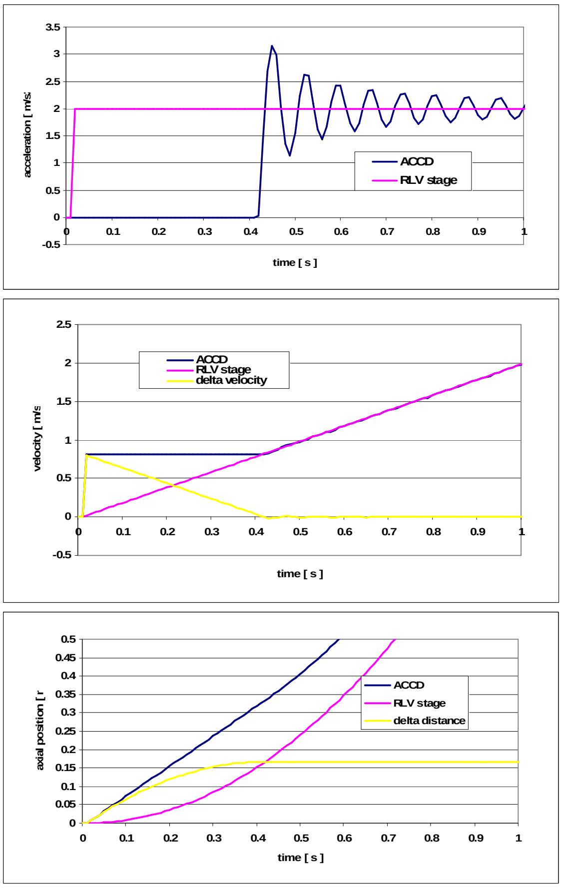

Figure 15: Dynamic reaction of towing rope tautening shock acting on ACCD in preliminary test case

4.3 Recalculation of load case 1 under consideration of the load case 2 dimensioning

After the pre-dimensioning of the tautening suspension system by dynamic simulation in the last section, the load case 1 has to be revisited taking into account the required helical spring system stiffness and damping coefficients. Simulations show that the direct coupling displayed in the model of Figure 12 would result in unintended damping behavior of the capturing shock. The two suspension systems for the two load cases are to be designed for such different load levels that a total decoupling is advisable. Figure 16 shows a new homologous model where the former helical spring system is disconnected from the ACCD mass. This might be realized by a disk or plate spring instead of the helical springs which should only be effective when compressed under the situation of load case 2. The initial conditions already described in section 4.1 are reused without modification.

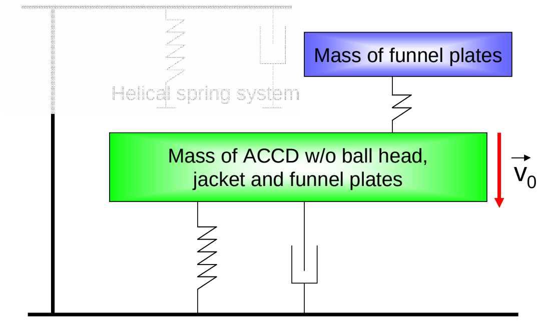

Figure 16: Homologous dynamic model of capturing shock acting on ACCD with new design of helical spring system no longer effective

After further taking into account realistic spring coefficients for the funnel plates which constrain their relative motion within less than 1 cm, a new simulation with unchanged characteristics of the industrial shock absorber has been carried out. Figure 17 shows the strongly different dynamic reaction compared to Figure 13. The deceleration of the ACCD is almost similar to the previous design and thus according to the intention. The amplitude and frequency of the funnel plate oscillation is significantly increased due to the increased stiffness of their spring suspension. These values do represent acceptable kinematic and dynamic conditions.

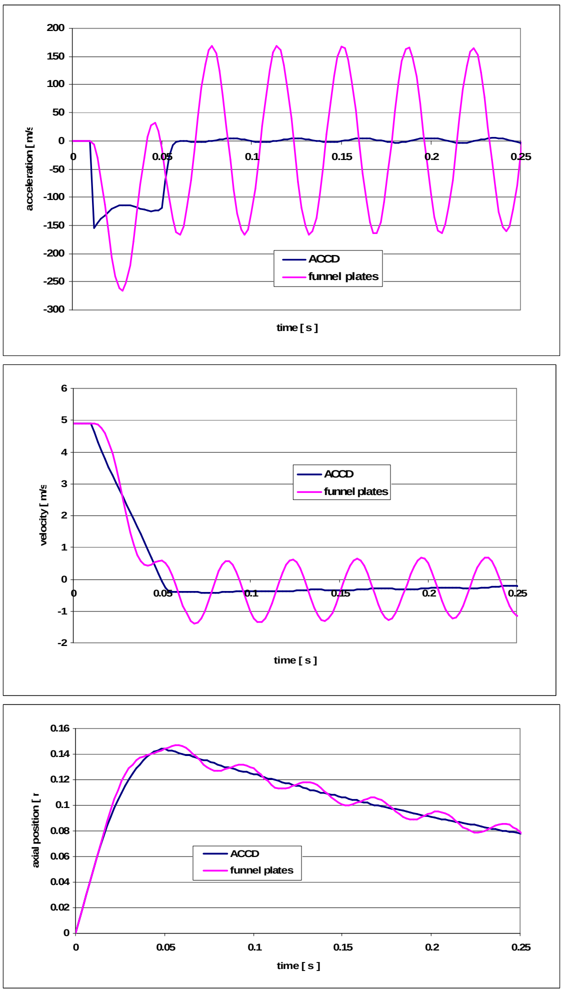

Figure 17: Dynamic reaction of capturing shock acting on ACCD after iterated design

5 CONCLUSIONS

The innovative method for the return to the launch site of reusable winged stages by in-air-capturing is briefly described and its major advantage of increased payload mass to orbit is quantified. The possible performance gain of the in-air-capturing method, as calculated in detailed simulations of selected example cases, offers an increase of at least 15 % payload mass into GTO compared to conventional fly-back with on-board propulsion and propellant. Alternatively the dry mass of the reusable stage can be reduced by 17 % without loss in reference payload, hence considerably decreasing the size and cost of the vehicle.

The selected flight strategy and the applied control algorithms show a robust behavior of the reusable stage to reach the capturing aircraft. In the nominal case the approach maneuver of both vehicles requires active control only by the gliding stage. Simulations (3 DOF) regarding reasonable assumptions in mass and aerodynamic quality proof that a minimum distance below 200 m can be maintained for up to two minutes.

The most promising capturing technique is using an aerodynamically controlled capturing device (ACCD), showing the best performance and lowest risk. Therefore a capturing mechanism has been preliminarily designed for the ACCD. The principle idea of the mechanism design with its major conditions and constraints is described in the paper. The structural parts have been pre-dimensioned for two static load cases supported by finite element calculations. Component masses are obtained with some iterative resizing.

In the next step the two dimensioning load cases which experience significant shocks are dynamically simulated. In a simplifying approach a dynamic system simulation tool is used with a strongly limited number of discrete elements. This methodology allows for rapid parametric analyses of component properties selection and for the convenient assessment of required design improvements. The analyses reveal that a full decoupling of the two suspension systems will be required, each to be separately adapted for its dynamic load case. Technical solutions exist and will be implemented in the forthcoming design refinement of the in-air-capturing mechanism.

In the last two years the unusual in-air-capturing procedure has made further progress in its theoretical simulations and a preliminary design of the mechanism has been worked out. Confidence in the feasibility of in-air-capturing is strong and it seems unlikely that severe problems might one day be detected, which definitely would exclude its operation. The next steps should be component testing and (most important) subscale flight demonstration to raise the currently still low technology readiness level (TRL). The therefore required effort is moderate and worth the expenditure because in-air-capturing is able to strongly boost RLV performance and it offers a tremendous potential of operational improvements. Any comment and suggestion will be highly appreciated by the authors.

6 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of Ms. Bärbel Schlögl who performed a large part of the capturing simulations and of Ms. Jeannette Heide who worked on the design of the 'in-air-capturing'-mechanism.

7 REFERENCES

1. Sippel, M., Klevanski, J.; Kauffmann, J.: Innovative Method for Return to the Launch Site of Reusable Winged Stages, IAF-01-V.3.08, Toulouse 2001

2. Sippel, M., Klevanski, J.: Progresses in Simulating the Advanced In-Air-Capturing Method, 5th International Conference on Launcher Technology, Missions, Control and Avionics, S15.2, Madrid, November 2003

3. Patentschrift (patent specification) DE 101 47 144 C1, Verfahren zum Bergen einer Stufe eines mehrstufigen Raumtransportsystems, released 2003

4. Klevanski, J.; Sippel, M.: Beschreibung des Programms zur aerodynamischen Voranalyse CAC Version 2, SART TN-004-2003, DLR-IB 647-2003/04, March 2003

5. Covault, C.: Astronaut Skills Honed Flying Steep STA Dives, in Aviation Week & Space Technology, July 8, 2002

6. Dietlein, I.; Prel, Y.; Bonnal, C.; Polti, S.: Staging and Mission Analysis for a Future Launcher Concept with a Reusable First Stage, IAC-04-V.8.06, October 2004

7. Schlögl, B.: Systematische Analyse von Ankopplungsverfahren zum Bergen einer wiederverwendbaren Raumtransporterstufe in der Luft, SART TN-008/2003, DLR-IB 647-2003/11, October 2003

8. Heide, J.: Auslegung eines Kopplungsmechanismus für das In-Air-Capturing Verfahren, SART-TN 004/2005

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