Innovative Method for Return to the Launch Site of Reusable Winged Stages

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This paper proposes a new, and different approach for return to the launch site of non-SSTO reusable space transportation vehicles. 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 (patent pending) is initiated by large cargo transports, offering sufficient thrust capability to tow a winged launcher stage with restrained lift to drag ratio. Technical requirements of the tow-aircraft indicate, that (depending on the stage's size) an Airbus A-340 or B-747-class jet offers good thrust margins. The performance gain by the advanced capturing method shows a possible increase in delivered payload between 15 % and 25%, assuming the same structural technology level of the stages. Alternatively, the size of a reusable system can be significantly reduced compared to the standard approach, without any loss in payload mass.

The paper presents a detailed description of the proposed method, giving data of numerical simulations regarding the nominal mission. A comparative analysis, looking also at conventional systems quantifies the advantages. The second part of the paper proofs the viability of the proposed in-air-capturing method by regarding its off-design performance. Assuming different perturbations of the normal flight, including a change in atmospheric wind or slightly different stage-separation conditions. Analysis shows the flight dynamic potential of the descending vehicle to dissipate energy to be quite comfortable.

Nomenclature

D	Drag	N
H	altitude	m
M	Mach-number	-
S	distance	m
T	Thrust	N
V	velocity	m/s
W	weight	N
k	control system coefficients	s^{-1}
n	load factor	-
q	dynamic pressure	Pa
α	angle of attack	-
γ	flight path angle	-
ε	part signal of control	s^{-1}
η	geometrical angle	-
σ	bank angle	-
ψ	azimuth	-

Subscripts, Abbreviations

3 DOF	three degrees of freedom
CAD	computer aided design
GLOW	Gross Lift-Off Weight
GTO	Geostationary Transfer Orbit
IR	infrared
LEO	Low Earth 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
TSTO	Two Stage to Orbit
AC	(capturing) aircraft
R	reserve
WS	winged stage
As	assigned
Sep	separation

1 INTRODUCTION

One major problem in the introduction of multiple stage reusable space transportation systems, is to find 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, all of today's 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 obligate a propulsion system and its fuel, which raises the stage's inert mass. If the rocket main engines should be re-ignited, one faces the poor specific impulse of such systems resulting in a (in terms of mass) prohibitively expensive amount of propellant just for decelerating. Usually a more attractive solution to the problem seems to be, to integrate a second type of air-breathing propulsion, reducing the propellant mass by an order of magnitude but adding the weight of the additional engines.

Moreover, the propulsion based approach is inherently risky, since the engine ignition has to be assured under adverse conditions and a very tight time gap.

This paper proposes a new, and different 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 initiated by large cargo transports, offering sufficient thrust capability to tow a winged launcher stage with restrained lift to drag ratio.

2 MATHEMATICAL MODEL OF THE SIMULATION

The launch vehicle's ascent trajectory and ballistic flight phase is calculated by a standard 3 DOF optimization and simulation program. The flight path regards the usual constraints of safety, dynamic pressure, and heat flux. Since this approach is fully consistent with all other launcher analyses, it is not further described here.

The mathematical model used for the simulation of the capturing procedure includes a complete set of nonlinear movement dynamical equations in three dimensional space of both vehicles (the winged reusable stage and the capturing aircraft) with atmospheric simulation and a mathematical model of the winged stage's control system in modular structure.

3 DESCRIPTION OF THE PROPOSED IN-AIR-CAPTURING METHOD

This chapter presents a detailed description of the proposed method, giving data of numerical simulations regarding the nominal case.

3.1 Principal 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-cylinder', which is a large air-space column of several thousand meters in altitude. After its MECO the reusable stage is separated from the launch vehicle, and afterwards performs a ballistic trajectory, soon reaching denser atmospheric layers. There 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.

Regarding the method proposed here, 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, actively controlled by aerodynamic braking due to higher initial velocity and a steeper flight path. The capturing itself is accomplished at an optimum distance by the harpoon principle, shot from the aircraft. 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 3000 m. The upper constraint is set by the requirement to reach full aerodynamic controllability of the winged stage, which is found to cause some time delay. 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.

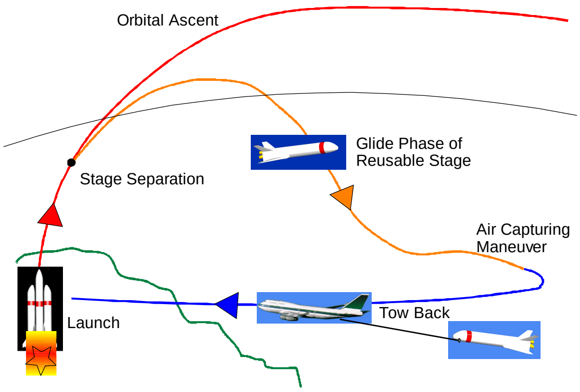

Figure 1: Schematic of the proposed capturing procedure in air-space

Basic assumption is, that 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.

3.2 Approach and Capturing Process

After deceleration to subsonic speed in 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 which corresponds to the equivalent earth speed 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 reaching the denser atmospheric layers, the winged stage employs for aero-dynamic control: the angle of attack α, the trajectory bank-angle σ, and the air-brake deflection angle δ_{FB} are used as control parameters. The speed brake is assumed to be of Space Shuttle rudder type. This should be achieved as far as possible without major interference on each other, acquiring 'quasi-independent' parameters.

The stage's navigation system computes the assigned flight azimuth ψ_{as}, which should always point at the capturing aircraft, the current distance, and the altitude difference between both vehicles. The control system of the winged stage realizes the following control law regarding the lateral movement:

$$\dot{\sigma} = k_{\psi}\,(?_{as} - ?) + k_{\sigma}\, n_z \sin\sigma \qquad \text{(equ. 1.)}$$

$$|\dot{\sigma}| \le 10°/s$$

where k are suitable control system coefficients, and n_z and ψ are the current flight parameters. The realization of this control law results in a precise heading of the reusable stage in direction of the capturing aircraft, and is maintained until capturing.

The winged stage firstly glides with a very steep angle γ_{gl} (e.g. around -18°) and reduces gradually its velocity, while the capturing aircraft flies in the flight level H ≈ 8 km with the constant equivalent velocity VEAS ≈ 400 km/h (Mach-Number M ≈ 0.55).

The control system stabilizes the flight path angle by adaptation of α:

$$\dot{\alpha} = \varepsilon_{\gamma} + \varepsilon_{n_z}; \quad \text{with} \qquad \text{(equ. 2.)}$$

$$\varepsilon_{\gamma} = k_{\gamma}\,(\gamma_{gl} - \gamma); \quad |\varepsilon_{\gamma}| \le 0.15°/s;$$

$$\varepsilon_{n_z} = k_{n_z}\,(\cos\gamma - n_z); \quad |\varepsilon_{n_z}| \le 0.1°/s;$$

with current flight data n_z and γ, and the control system coefficients k as well as partial control functions ε. Further the control system of the winged stage permanently computes the vertical geometrical angle η, which represents the angle between the line of sight of the two vehicles and the local horizon

$$\eta = \arcsin\frac{\Delta H}{\Delta S} \qquad \text{(equ. 3.)}$$

where ΔH is the current altitude difference and ΔS is the current total distance.

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 simulation described hereafter a descent gliding of both vehicles is chosen, with a flight path angle γ_{capt} slightly below the maximum L/D ratio of the winged stage. The more or less parallel descending of both vehicles enables a smoother approach maneuver, and 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 it 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.

The absolute value of the angle between both vehicles η decreases gradually during descent. At the instant when this angle becomes smaller than the winged stage's glide path ($|\eta| < |\gamma_{gl}|$), the capturing aircraft receives a signal from the reusable stage to also start its descent flight at a pre-chosen capturing angle $\gamma_{as} = \gamma_{capt}$. The launcher stage itself adapts the path angle such, to follow the capturing aircraft. As a result, after a short time both vehicles fly in line with an inclination angle corresponding to the chosen capturing glide path angle.

The winged stage follows the capturing aircraft reducing its distance ΔS and its velocity V. The control law is the following:

$$\gamma_{as} = \arcsin\frac{\Delta H}{\Delta S}; \qquad \text{(equ. 4.)}$$

$$\dot{\alpha} = \varepsilon_{\gamma} + \varepsilon_{n_z}; \quad \text{with} \qquad \text{(equ. 5.)}$$

$$\varepsilon_{\gamma} = k_{\gamma}\,(\gamma_{as} - \gamma); \quad |\varepsilon_{\gamma}| \le 0.15°/s;$$

$$\varepsilon_{n_z} = k_{n_z}\,(\cos\gamma - n_z); \quad |\varepsilon_{n_z}| \le 0.1°/s;$$

$$\dot{\delta}_{FB} = \varepsilon_{v} + \varepsilon_{n_x}; \quad \text{with} \qquad \text{(equ. 6.)}$$

$$|\dot{\delta}_{FB}| \le 30°/s; \quad |\delta_{FB}| \le 90°$$

$$\varepsilon_{v} = k_{V}\,(V_{ws} - V_{AC} - \Delta V_R);$$

$$\varepsilon_{n_x} = k_{n_x}\, n_x;$$

$$\Delta V_R = k_R\, \Delta S; \qquad \text{(equ. 7.)}$$

where δ_{FB} is the deflection angle of the air-brake, and V_R is the assigned excess or reserve velocity of the stage. Note, that equation 5 is different from equation 2 because the flight path angle γ_{as} is unlike the initial glide angle γ_{gl}.

The approach maneuver has been simulated for different reusable stages (see chapter 4 for type description) according to the above explained method, and the control constraints are applied. An example of a reusable stage with separation velocity around 2 km/s is described here. Figure 2 depicts the trajectory data altitude vs. time, and geographical position of both flight vehicles from launcher separation to the accomplished capturing. At first the winged stage performs its ballistic flight, followed by a common glide slope with the aircraft right after 675 s. At this time the geographical distance between them is less than 5 km.

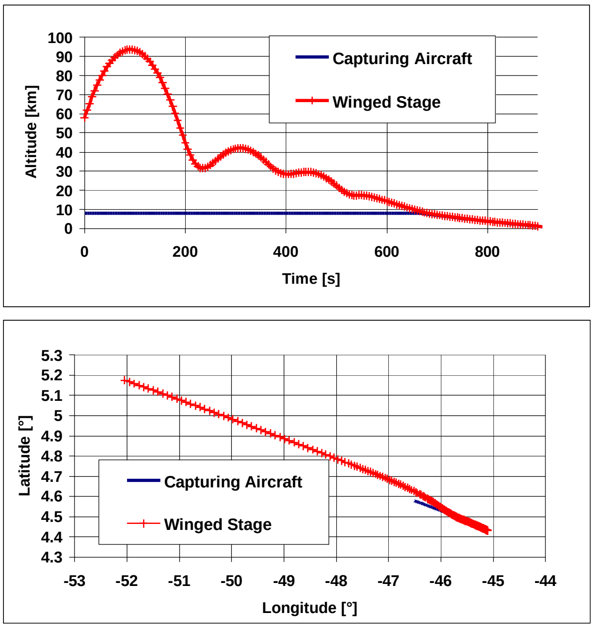

Figure 2: Simulation of the reusable stage's approach procedure to the capturing aircraft starting with launcher separation

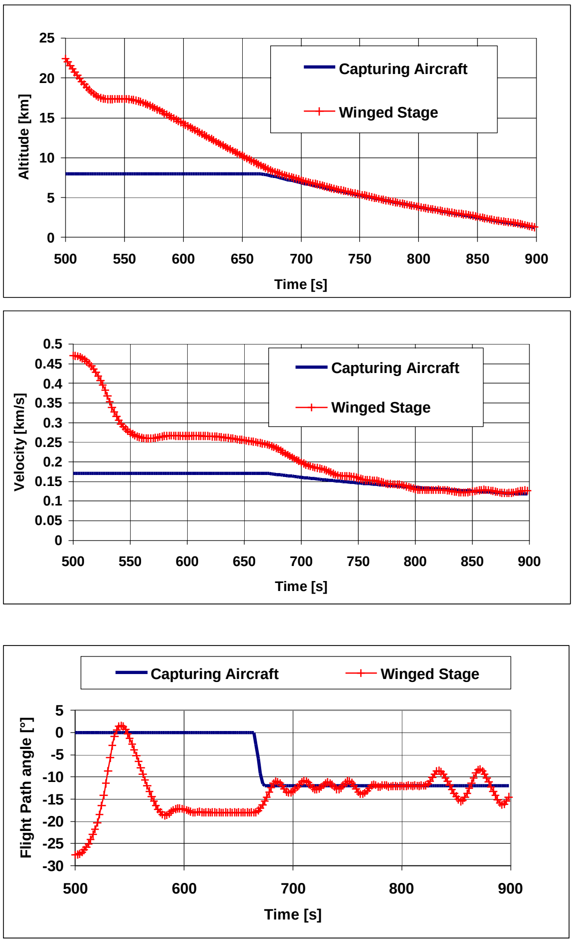

Figure 3: Simulation of the reusable stage's final approach procedure to the capturing aircraft starting 500s after separation from launcher

The aerodynamically controlled approach as shown in Figure 3 is initiated, when the reusable stage reaches the denser atmospheric layers and decelerates to the subsonic regime. The steep glide angle of around –18 degrees is performed with a nearly constant air speed of 265 m/s. After the capturing aircraft has received the appropriate signal, both vehicles are descending on nearly the same glide slope (670s). As can be clearly seen, the returning stage is still the active vehicle, since it is subject to some control deviations in flight path angle γ_{capt}. In parallel the winged stage actively reduces velocity up to the point where its minimum safety distance is achieved.

As can be seen from Figure 4, the total distance between the two flying craft falls short 1 km around 700 s after separation. Subsequently the distance could be controlled in this simulation at a minimum range between 180 and 400 m for a duration of 150 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 1.3 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 3.5 km.

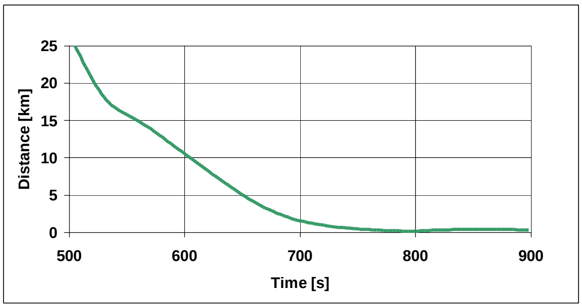

Figure 4: Total distance between the two stages in final approach procedure starting 500s after separation from launcher

Control deflection of the braking flap is shown in Figure 5. The brake type' effectiveness assumed is up to 25 % vehicle drag increase at full deflection. Due to the time delay for its actuation (30°/s), a simple single flap construction as assumed here is not able to precisely control the distance between both vehicles (see Figure 4). By supplementary integration of smaller, but faster flaps a better behavior should be achievable. To proof the principal functionality of the in-air-capturing concept such more sophisticated technology is not necessary to be regarded here.

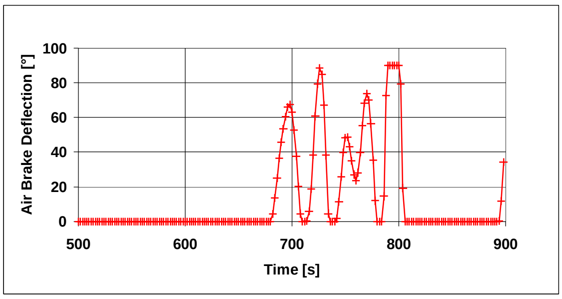

Figure 5: Air-braking deflection angle ϕ_B of reusable stage's final approach procedure

The capturing technique itself is not in focus of this paper. Up to now, no detailed simulation as for the approaching control has been performed. The process and the necessary mechanics are by far not optimized yet, but preliminary analyses offer several promising techniques. The most interesting imaginable procedures are accomplished by the harpoon principle.

At around 500 to 700 m total distance ΔS, a small pilot-rope is shot from the transport aircraft to the returning stage. The harpoon consists of an air-to-air IR-guided missile with attached capturing device and mechanics to rail the pilot rope. The rope is stored on a synchronized powered drum system, located in the aft compartment of the cargo transport. The missile mass, considerably increased by its payload, will only reach a final velocity in the high subsonic regime, which is beneficial for the loads during the device's impact at the launch vehicle's connecting point. As a result the delivery duration of the harpoon will extend between 4 and 5 s. A possible design for the connecting point is shown in Figure 6. The annular structure is lowered from the reusable stage's nose section. Such a design allows the powered missile to fly through the hole after detaching the capturing device. The missile’s approach parallel to the stage’s fuselage should be achievable avoiding collision with the RLV. A shock absorbing spring construction on the stage and the capturing device is to be designed to withstand relative velocities up to 300 m/s.

After achieving the primary connection, a strong towing rope is drawn out, while the winged stage is still approaching the carrier aircraft. At a certain minimum total distance (between 100 and 200 m) the control system should prevent further approaching by full deflection of the air-brake on the winged stage. This is practiced mostly for safety reasons.

Available air-to-air missiles like AIM 9, Magic 2, R-73, or ASRAAM might be enhanced to find its target with multiple redundancy. A radar on the capturing device or an active transponder at the connection point of the returning stage are such improvements to help safely connect both flight vehicles.

Further steps in the investigation of the in-air-capturing method will provide more detailed data about dynamical behavior of the complex interacting devices, and the resulting loads. Several more sophisticated alternatives are already proposed at DLR-SART, which offer remarkable improvements and even larger margins. The initial effective distance might be reduced by deploying an aerodynamically controlled device, which is to be released and then towed by the airplane. This device contains the above mentioned harpoon mechanism and is used to support the approaching process via its onboard control. Reducing the flight distance for the missile, and adding degrees of freedom to the rope mechanisms, the loads should be decreased. Another possibility exists for the missile to perform a loop maneuver, and approach the connection ring from the opposite direction as that shown in Figure 6. In this case the impact loads can be considerably reduced, due to the lower relative velocity between harpoon and the to be captured stage.

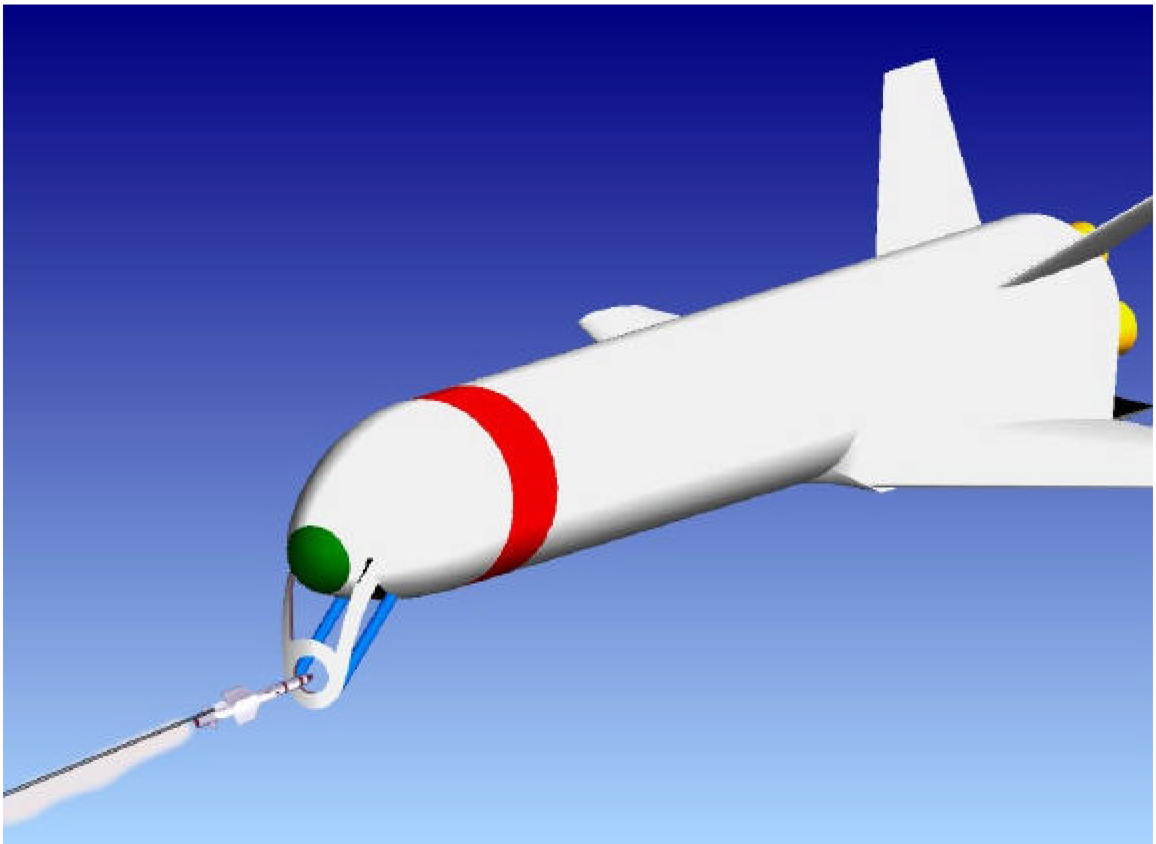

Figure 6: Principal sketch of a conceivable connecting procedure with approaching missile and connecting point of the reusable stage in deployed position

3.3 Tow-Back Requirements

Technical requirements of the tow-aircraft mainly involve installation of the rope mechanism, availability of sufficient thrust, and in some special cases probably additional spoilers to act as aerodynamic speed brakes.

The rope and its mechanism has to be designed to withstand the pulling stress with regard to dynamic loads. The maximum values are most likely be reached during pull-up of the assembly after capturing.

The thrust requirements of the capturing aircraft are dependent on the reusable stage's mass and its L/D-ratio. The reentry mass of a winged booster stage includes the dry mass, and – if not drained - propellant residuals and reserves. This may account for a mass between 25 and 80 Mg. A trimmed subsonic L/D of blunt stages with low aspect ratio of about 4 to 5 is achievable [2]. The thrust reserve of the capturing aircraft therefore has to exceed 50 to 200 kN in an adequate flight altitude. Before performing a detailed analysis, it can be stated, that a four engine jetliner without normal cargo loading offers sufficient thrust margins. This is corresponding to an Airbus A-340 or B-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. There should be no disadvantage in operating used airliners for the in-air-capturing role, because the daily flight hour demand is modest.

4 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 calculations are based on detailed simulations, assuming the same structural technology level of all regarded stages, to be compared. Detailed mass models and ascent optimization are included in the investigation. Nevertheless, it was not possible within this study to fully iterate the design of the advanced reusable stages. It is quite likely, that further optimization potential exists for the captured launch vehicles.

4.1 Medium Separation Velocity

The first quantified assessment of the advantage is performed for a reusable first or booster stage with a separation Mach number around 2 km/s. The analyses are based on symmetrical liquid booster configurations attached to a future upgraded Ariane 5 expendable launcher. Such vehicles had already been intensively investigated by DLR-SART [1]. The reference booster is a LOX-RP1 powered winged stage using kerosene fuel for the fly-back mission. A heavy lift double launch into GTO is regarded.

Three sub-variants of the in-air-captured stage are considered, all derived from the original JP-powered fly-back configuration:

A. Abolishment of all turbojet engines, their thrust structure, propellant supply, JP-tanks, and fuel. Addition of a special connecting structure, and special communication equipment with the capturing aircraft. Due to the considerably reduced separation and atmospheric reentry mass (-28%), the wing is linearly reduced in size by a factor of 0.9, which is a conservative approach.

B. Abolishment of the turbojet equipment and fuel as in A, while keeping the launcher's original thrust-to-weight ratio at lift-off. This can easily be achieved by adding propellant for the rocket engines, burnt during an extended boost time. An enlargement of the tanks about 5 % is included. Although the reentry mass is reduced, the wing size is unchanged to the reference vehicle to take into account higher reentry loads due to increased separation conditions.

C. The aim of this configuration is to keep the payload mass of the reference configuration unchanged, while significantly reducing the size of the reusable booster stage. Beside the measures already implemented in A and B, the ascent propellant mass can be reduced, enabling the contraction in tank, body, wing, fin, and control flap sizes. This might be of interest to minimize development as well as operational cost of the reusable stage.

The resulting payload performance is increased by around 15 % for the variants A and B as shown in Figure 7. Note, that case B is only about 1.5 points above A, since in the regarded configuration only a slight increase in RLV ascent propellant mass is achievable.

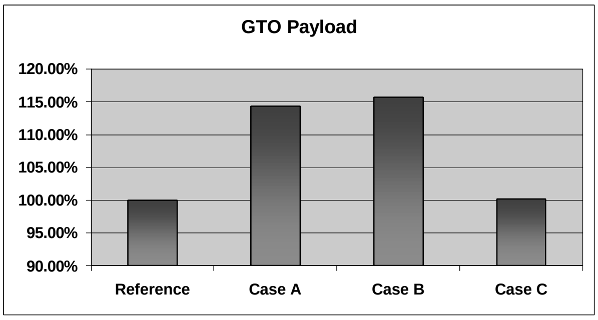

Figure 7: Comparison of GTO payload of different to be captured stage concepts (A through C) with conventional jet powered fly-back stage (reference)

The to be captured stages offer a dry mass reduction of more than 10 % just by the abolishment of air-breathing engine equipment. If the size of the RLV is considerably reduced, holding payload constant, at least 17 % diminishing of mass is achievable (Case C) in a still conservative assumption. (see Figure 8) The decrease in separation mass is even stronger (up to –30%), since there is no need for fly-back propellants. This will have a positive effect on the vehicle's reentry loads, strongly depending on the hypersonic wing loading[1]. The lift-off mass of case C is reduced by more than 20 %, due to the lower ascent propellant mass. In case B this mass is slightly below the reference value, since the requirement of same launcher lift-off thrust-to-weight ratio has to be regarded with respect to an increased payload mass.

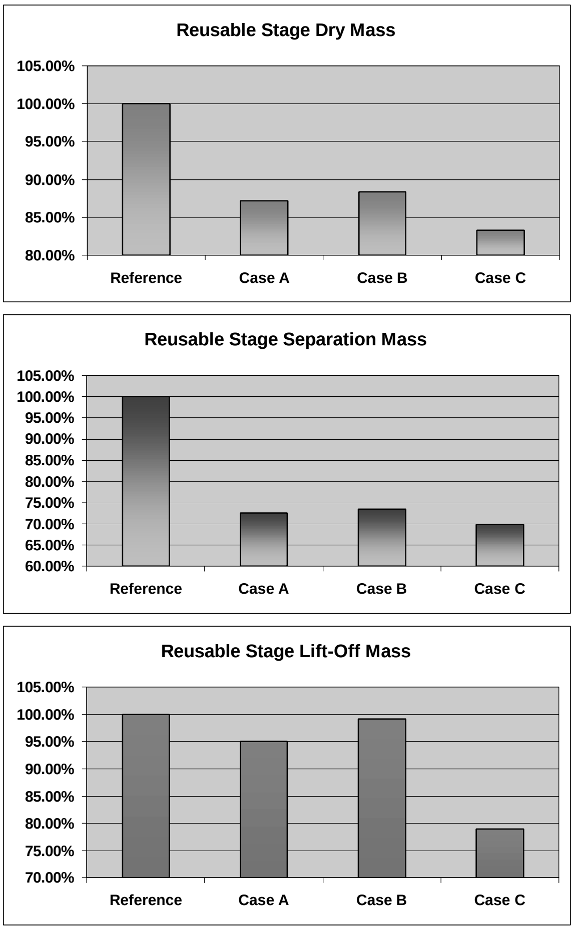

Figure 8: Comparison of various masses of different to be captured stage concepts (A through C) with conventional jet powered fly-back stage (reference)

4.2 High Separation Velocity

It is of further interest to analyze, if the proposed in-air-capturing method offers also advantages for a reusable stage of considerably higher separation velocity. Such launch vehicles are usually not to be designed to perform a direct fly-back to the launch site, since the required fuel is beyond any reasonable amount.

If possible, they try to avoid any secondary propulsion system and to reach a downrange landing site. Several proposals for such reusable sub-orbital stages exist, all relying on the availability of such a landing field. As mentioned in the introduction, they are very rare, and to be able to reach them under adverse conditions will pose a notable challenge. However, such launch vehicles are to be designed to reach one or more of these landing sites with sufficient margins. The negative impact on their trajectory and payload performance is difficult to assess here, since it is strongly dependent on specific data of the proposed vehicle. Obviously, in case of a change in destined inclination of the payload, the performance will be influenced by the return trajectory requirements of the reusable stage.

To have a look at the same attractive commercial geostationary orbit as in chapter 4.1, a launcher programmatic sample is to be investigated. Assuming the launch vehicle is exactly defined, that the reusable stage is able to reach its nominal landing site, then it is also required, that the expendable upper stage's size and attached payload mass has to stay within tight limits. If this is not assured, the reusable vehicle will have no prospect to arrive at its landing field. This is a severe restriction for the development of a growth version of the launcher, which usually is initiated to significantly reduce specific launch cost.

The reference launcher of this chapter consists of a winged reusable LOX/LH2 stage with a separation velocity close to 5 km/s, and an expendable cryogenic upper stage. The reusable vehicle is assumed to be able to reach a down range nominal landing site in a simple glide trajectory. Two sub-variants of an in-air-capturing stage, derived from the reference configuration are regarded:

D. The same reference reusable stage, but including the necessary capturing devices connecting structure and communication equipment, and same expendable upper stage.
E. A more interesting approach, relying on the reusable configuration exactly as in D, but accelerating a considerably more powerful, propellant and thrust enhanced orbit delivering stage.

As to be expected, the D configuration delivers a slightly reduced payload (-2.5 %) to orbit due to the increased first stage's inert mass. Nevertheless, it offers the opportunity to directly return the reusable stage to its launch site, reducing operational expenses and turn-around time. It should be noted, that the degraded performance of example D is very theoretical, since it assumes, that the reusable stage's reference landing site position is fully optimized, which usually is impossible to achieve.

Figure 9 shows the possibility of strongly boosting payload performance to GTO by 25 % using the same in-air-capturing stage, and a thrust and propellant increased upper stage (case E).

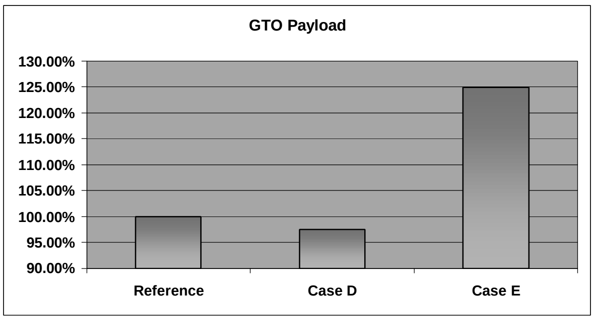

Figure 9: Comparison of GTO payload of to be captured stage concepts D and E with conventional unpowered glide stage (reference)

Such a growth version can most likely only be realized with an in-air-capturing stage, because the separation conditions will be notably reduced due to the increased upper stage's mass. As a consequence the range is degraded by 25 % or 600 km (Figure 10), posing insurmountable problems for a reusable vehicle to safely reach its landing field. This is true, unless in the unlikely cases where an alternate, closer landing site can be found or the reusable stage is largely oversized right from the beginning.

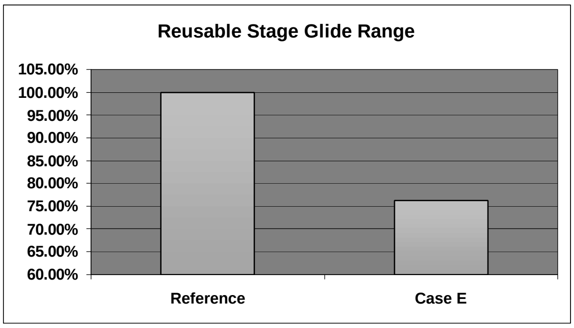

Figure 10: Comparison of glide distance of to be captured stage concept E with conventional unpowered glide stage (reference)

A comparison of mass in Figure 11 depicts a slight increase (1.8 %) in dry mass of the in-air-captured vehicles (D, E) due to their special equipment. Launcher lift-off mass of variant E modestly rises by 3.4 %, which is mostly due to the larger upper stage and higher payload mass. Such an increase is acceptable for the launcher itself, only requiring the safe atmospheric reentry of the reusable vehicle.

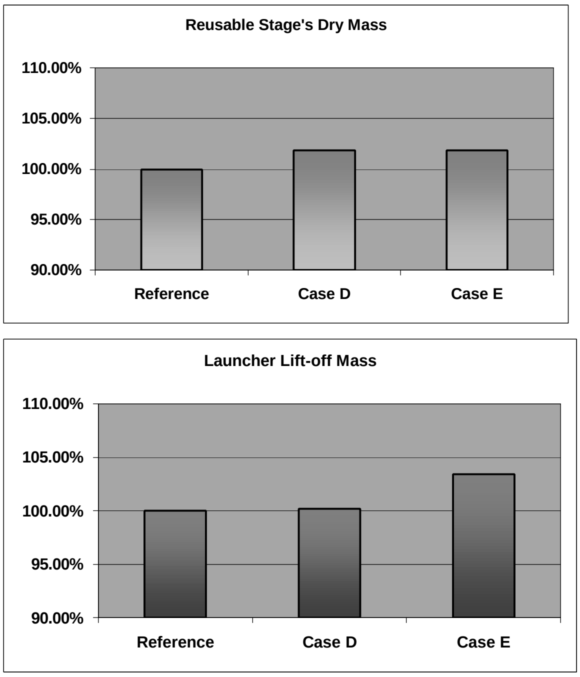

Figure 11: Comparison of the reusable stage's dry mass and launcher GLOW of to be captured stage concepts D and E with conventional unpowered glide stage (reference)

5 ROBUSTNESS OF THE PROPOSED METHOD REGARDING ADVERSE CONDITIONS

This part of the paper proofs the viability of the proposed in-air-capturing method by regarding its off-design performance. Assuming different perturbations of the normal flight, including a change in atmospheric wind or slightly altered stage-separation conditions.

Variations of different to be captured stages show, that the RLV should have a horizontal distance to the capturing aircraft of about 20 km, when starting aerodynamically controlled descent at 20000 m altitude. An acceptable longitudinal and lateral deviation of +/- 2 km can be compensated only by the returning stage, while the aircraft stays passive in nominal mode.

Without correction, unexpected adverse conditions will produce larger deviations, which can not be compensated during the final approach maneuver of the returning stage. These are notably a wind speed at sea level of 15 m/s (deviation +/- 8 km) or a separation condition considerably below the nominal case (deviation around +/- 20 km). But suitable correction maneuvers are well within reach. The flight dynamic potential of the descending vehicle to dissipate energy earlier in the trajectory is – depending on the specific design - quite comfortable. Even under the most critical circumstances, when separation time varies about 1.5 seconds for the high velocity RLV (case E of chapter 4.2), the stage should be able to reach its regularly foreseen rendezvous area, while staying within the loads envelope. This can be achieved for example by limiting the maximum normal acceleration n_z to 3.2 instead of 3.5 g, if maximum design dynamic pressure is not exceeded. Banking maneuvers also offer some potential to sufficiently correct the stage’s place.

Since the capturing aircraft has an own capability to improve its geographical position, further margins exist. Tracking of the returning launch vehicle is always possible by radar, or satellite, and is communicated via direct data link. Wind conditions are meteorologically well known and can permanently be updated by the waiting airliner. Therefore, a real-time optimization of the aircraft's position is manageable. Since the ballistic phase of the stage extends to several hundreds of seconds, an adjustment of up to 100 km is achievable.

6 OPTIMIZATION POTENTIAL

The proposed in-air-capturing method is still at a very early stage of development. Nevertheless, some optimization potential can already be identified. Beside the complete capturing mechanism, two major issues should be addressed.

Chapter 3.2 demonstrated in principal the controllability of the returning stage to approach the capturing aircraft. One major element to achieve success are the braking control flaps. A smoother approach maneuver is possible by integrating smaller but faster and more sophisticated secondary flaps on the stage. As a result static and dynamic loads on the vehicles and the ropes are reduced. If a powerful aerodynamic control system exists, further optimization of the capturing software is imaginable.

The requirements of the capturing and towing airliner has not been deeply investigated. This is due to the fact, that it plays a more or less passive role in the whole procedure. One question of concern might be that of crew safety in an aircraft performing a *near* midair collision. Such an event 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 to also redesign the capturing and towing aircraft as an unmanned aerial vehicle. This is not such an exotic idea, if one realizes, that even combat training missions are flown unmanned by converted F-4 fighters[3]. 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.

7 CONCLUSIONS

An innovative method for the return to the launch site of reusable winged stages by in-air-capturing has been proposed and analyzed. The major advantages demonstrated in this paper, are increased payload mass to orbit, and better and safer operational characteristics.

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. The available time to achieve full connection is strongly dependent on the aerodynamic and flight mechanic characteristics of both vehicles, as well as the chosen flight strategy. Simulations (3 DOF) regarding reasonable assumptions in mass and aerodynamic quality proof, that a minimum distance below 500 m can be maintained for at least one minute. Further decreasing the minimum acceptable flight level might enable a duration of up to two minutes.

Development of the connecting devices itself is not in focus of this paper. Nevertheless, some preliminary ideas are proposed, which offer quite good margins to be implemented in a real system. All are based on a guided missile accelerating a harpoon device to connect the towing rope with the returning stage. More detailed analyses of the dynamic behavior should be accomplished in the future.

The possible performance gain by the advanced capturing method is calculated in detailed simulations of selected example cases. Reusable stages with separation velocity 2 km/s and close to 5 km/s are regarded, representing the range of the in-air-capturing highest effectiveness. Introducing the new method instead of autonomous fly-back with on-board propulsion and propellant, offers an increase of at least 15 % payload mass into GTO. Alternatively the dry mass of the reusable stage can be reduced by 17 % without loss in reference payload, hence considerably decreasing the size of the vehicle. A reusable vehicle with nominal downrange landing site usually is severely restricted by their availability. The introduction of a launcher growth version with a more powerful upper stage, but continuously using the same reusable in-air-captured first stage can achieve a calculated 25 % increase in GTO payload. Due to the landing field restrictions, the reference conventional glide vehicle usually is unable to come any close.

Analyses of off-design performance show, the flight dynamic potential of the descending vehicle to dissipate energy to be 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. Since the capturing aircraft has an own capability to improve its geographical position, further margins exist. Keeping this in mind, a high degree of safety, and reliability of the in-air-capturing method is to be expected.

The new and unusual procedure proposed here is neither flight proven nor fully dynamically simulated under all conditions. Some severe problems might one day be detected, which definitely would exclude its operation. Nevertheless, it can be stated, that it is able to strongly boost RLV performance, and offers a tremendous potential of further improvements. Any comment will be highly appreciated by the authors. The in-air-capturing method is open for discussion in the space transportation and launcher community.

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