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Full-scale simulations of 'In-Air Capturing' return mode for winged reusable launch vehicles

Full-scale simulations of 'In-Air Capturing' return mode for winged reusable launch vehicles

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Abstract. The recent success of reusable launchers has become a driving force for sustainable launch technologies. An innovative approach proposed by DLR, involves winged rocket stages captured mid air and towed back to the launch site by an aircraft. This recovery concept known as 'In-Air Capturing (IAC)', shows potential for substantial cost reduction, when compared to existing return modes. In the light of the Horizon 2020 project FALCon, full-scale simulations and sub-scale flight testing were carried out for further development of the technology. The paper summarizes the full-scale studies performed within FALCon. The full-scale test cases are introduced and the simulation framework for analysis of trajectories is presented. Then, the IAC maneuver is analyzed through trajectory simulations. Major external disturbances coming from the wake of the aircraft and flexibility of the rope connecting the rocket stage to the aircraft (after capture) are also addressed.

1. Introduction

Over the past decades, the growth of the commercial launch industry has brought about a renewed interest in reusable launch systems. Reusable Launch Vehicles (RLVs) have become instrumental to meeting the increasing launch demands at a reduced cost. Most of the RLVs currently in service, focus on the recovery of the first stage via Downrange Landing (DRL) or Return To Launch Site (RTLS) [1]. These launcher stages rely on descent propellant for slowing down and landing vertically. The extra fuel needed for landing adds to the take-off mass of the system and takes away from the payload capacity. Fly-Back Boosters (FB), which are powered by turbofans, also require an additional propulsion system for descent [2]. Other winged launch systems, similar to space shuttle, require a re-entry from orbit for sufficient momentum to return to the launch site. Hence, they are not a viable solution for recovery of boosters, which separate at a much lower altitude.

Some other technologies, which do not rely on extra propellant are also under investigation. Parachute based concepts like ballutes and mid-air retrieval (using helicopters) provide scope for reasonable cost savings for micro launchers. However, these technologies become impractical as the rocket stages get larger [3]. An innovative and effective method for recovery of a wide scale of launcher stages is the 'In-Air Capturing (IAC)' method. In this approach, a winged rocket stage is captured in a gliding trajectory mid-air and towed back to the launch site using an aircraft [3]. The IAC method was first invented and patented by DLR in 2003 [4].

To analyze the performance benefit of IAC, studies were performed in comparison with other RLV modes (like RTLS, DRL and FB) for the same mission of delivering 7.5 tons to GTO. Different propellant combinations and two types of engine cycles, gas generator and Staged

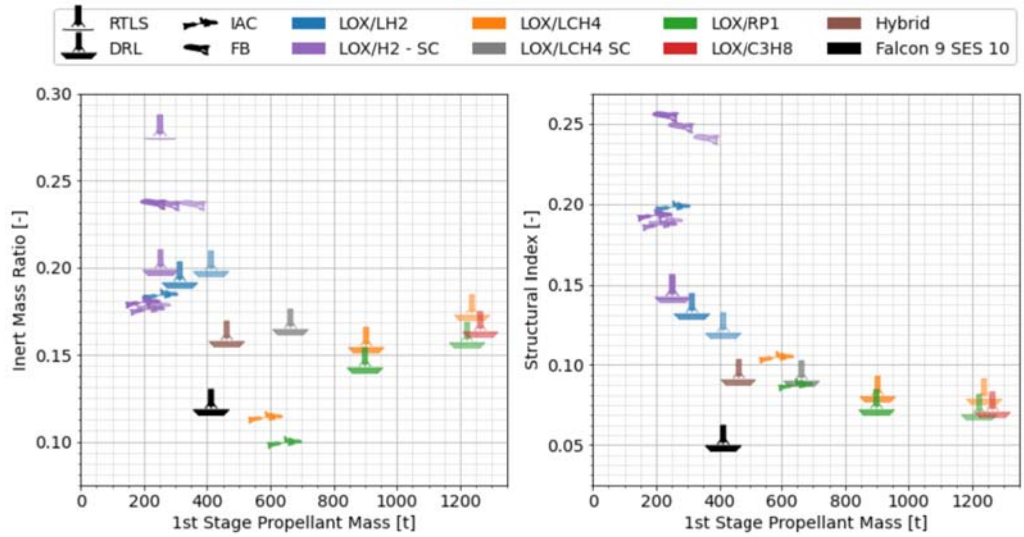

Figure 1: Comparison of Inert Mass for Different RLV Return Modes

Combustion (SC), were also considered [5]. The inert mass ratio and structural index were used as the main performance indicators. The inert mass ratio is the ratio of mass of the first stage at re-entry (residual mass) to the total mass during lift-off. The structural index is defined as the dry mass of the system to the total propellant mass it can carry. Both relations have simply been derived from the Tsiolkovsky's Rocket Equation. In Figure 1, the lower left region of both the plots indicate better design, while the upper left corner indicate lower performance. It can be seen that for all propellant combinations, IAC provides the lowest inert mass ratios. However, the structural index of IAC appears to be larger than the vertical landing methods. This is because IAC requires winged stages and additional hardware like landing gear, which lead to a larger structural mass. However, the disadvantage is surpassed by eliminating the need for descent propellant. This allows IAC based launchers to deliver the same payload with lesser propellant. Hence, there is a potential for substantial mass and cost reduction using IAC [6].

For further development of this technology, detailed investigation was performed under an EU-funded Horizon 2020 project called FALCon (Formation flight for in-Air Launcher 1st stage Capturing demonstration). The international project aimed at the research and development of IAC technology through both full-scale simulations and sub-scale flight demonstrations. In this paper, an overview of full-scale simulations and critical results obtained within the framework of FALCon are presented. In Section 2, the mission cycle of the IAC process and the selected test cases for full-scale simulation are presented. Then, the simulation framework and the trajectory simulations for controlled manoeuvres involved in IAC are analyzed in Section 3. Finally, the study is concluded and future work in discussed in Section 4.

2. Full-scale Mission Cycle

Figure 2 shows the generic schematic of a mission, where a winged booster is recovered using IAC. The mission starts with a vertical lift-off of the launch vehicle. The winged booster separates from the launch vehicle and re-enters the atmosphere after the Main Engine Cut-Off (MECO). During the re-entry, the vehicle slows down to a subsonic glide using atmospheric braking. Meanwhile, a suitably sized aircraft waits at about 10 km altitude around the potential capture zone. Once the RLV is in vicinity, IAC is performed between an altitude of 2 km and 8 km [7].

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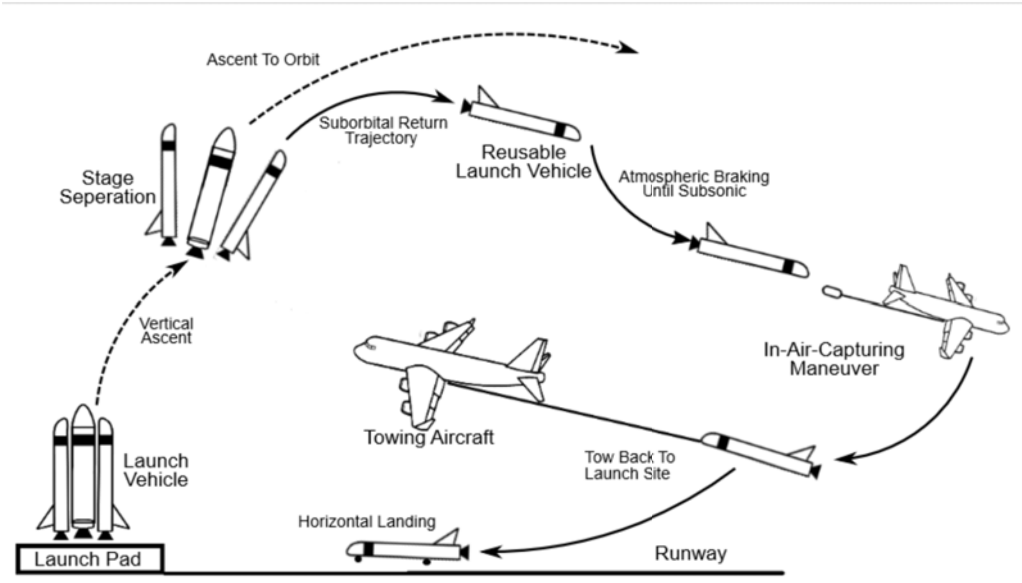

Figure 2: In-Air Capturing Mission Cycle

2.1. Phases of In-Air Capturing

To get a better understanding of maneuvers involved, the IAC process is divided into five phases:

(i) *Formation Flight*: The first phase begins when the RLV is sufficiently close to the awaiting Towing Aircraft (TA). The TA glides from cruise flight to achieve a parallel formation with the RLV. The vehicles try to maintain similar velocities, and a safe relative distance ranging between 150 m to 350 m. The TA during this phase must remain in front of the RLV. A detailed modelling of the subsystems and analysis of this maneuver can be found in [8].

(ii) *Capture Phase*: The capture phase takes place while the two vehicles are in formation flight. During this phase, a capturing device attached to a rope is released from the TA. The device trailing behind the aircraft (as shown in Figure 2) must autonomously navigate its way to the RLV and connect the two vehicles. This phase can be perceived similar to the air-to-air refueling application, which also uses capturing device with a hose to connect the tanker aircraft to the target aircraft [9].

(iii) *Pull-Up Maneuver*: Once the vehicles are connected via rope, the TA throttles up its engines. The mated vehicles attempt to pull-up from the descending flight to gain altitude and reach suitable cruise conditions. During this phase, the TA acts as an external propulsion system to the unpowered RLV.

(iv) *Tow-Back Phase*: The TA simply tows the RLV back to the launch site. During this phase, the TA engines counteract the drag of the RLV, while the RLV supports its own weight using the lift from its wings to maintain constant altitude.

(v) *Release Maneuver*: Close to the landing strip, the RLV is released by the TA. Finally, the RLV lands autonomously using its own landing gear as shown in Figure 2.

Within the framework of FALCon, the first three phases were studied in considerable detail using full-scale test cases. These phases are the most challenging and critical to the success of IAC. The tow-back is simply a cruise flight at more or less constant altitude and speed. The autonomous landing of winged stages has already demonstrated successfully in the past. This paper summarizes the results obtained during the study.

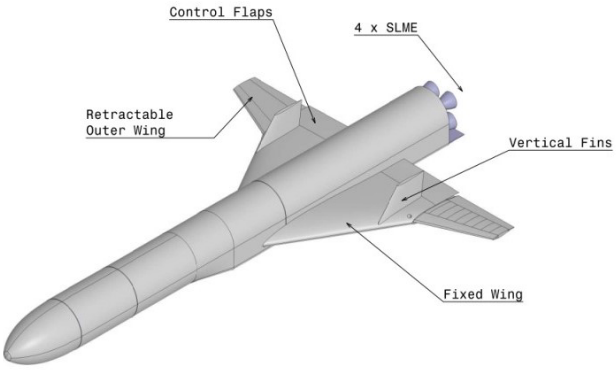

Figure 3: Reusable Launcher Stage - RLVC4

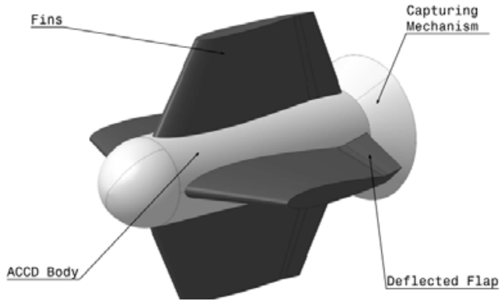

Figure 4: Capturing Device - ACCD

2.2. Full-scale test cases

One of the main advantages of IAC comes from the fact that the recovery method can be applied to wide range of winged launch systems. Based on the size of the target to be captured, a suitably sized aircraft must be selected. The capturing device used to connect the vehicles must also be designed to sustain the loads from towing a heavy launcher stage. For the current study, larger full-scale vehicles are selected to analyze the associated complexity. The three test cases selected for full scale simulations are:

- *Reusable Launch Vehicle (RLV):* The formation flight phase of IAC requires the two vehicles to have similar aerodynamic performance to maintain formation. Therefore, to maintain a long formation with an aircraft with high Lift-to-Drag (L/D) ratio, the RLV should be winged. This facilitates a higher L/D ratio in RLV. However, a large wing span in RLVs can lead to shock-shock interaction during re-entry. Therefore, a configuration with foldable outer wings is selected. Figure 3 shows the reusable launcher stage (called RLVC4) used for the full-scale scenario. With the outer wing deployed, the RLV can reach a L/D ratio up to 6. More detail about the vehicle can be found in [5]. The RLV is expected to weigh 80 tons during the descent.
- *Towing Aircraft (TA):* Based on the loading capacity and thrust requirements for capturing a large RLV, the retired Airbus jetliner A340-600 is selected. The long-range commercial aircraft with four powerful Rolls-Royce Trent 556 engines and relatively advanced flight control system fits the specifications for IAC. Additionally, using a retired aircraft facilitates cheaper acquisition costs and promotes reusability.
- *Capturing Device:* To be able to quickly span the gap between TA and RLV, the capturing device needs to be agile and maneuverable. Based on this requirement, an Aerodynamically Controlled Capturing Device (shown in Figure 4) is chosen. This capturing device, designed by DLR, constitutes a 2 m long body with large fins spanning 1.5 m in cross-section. The flaps at the end of the four fins can be deflected up to $\pm 15°$ and are used for 6DOF control of the device. The nose is connected to the TA via rope and the back of the device contains a capturing mechanism that locks on to the RLV on contact.

The trajectory simulations performed using these full-scale test cases are presented and analyzed in coming sections.

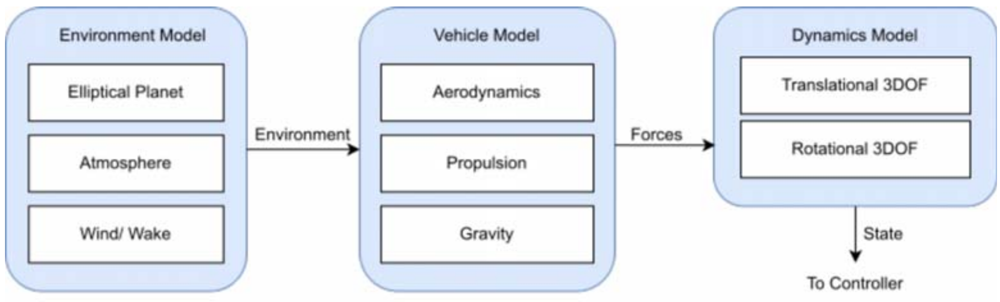

Figure 5: Dynamic Simulation Set-Up for Each Vehicle

3. Trajectory simulations

Preliminary trajectory simulations are performed for the first three phases of IAC - formation flight, capture phase and pull-up maneuver. The phases are analyzed and iterated individually in the current study to understand the complex dynamics and challenges involved. In future studies, the complete IAC process will be simulated and optimized together [10]. In the coming subsections, the simulation set-up is briefly described and then, the results are discussed.

3.1. Simulation Set-Up

For a realistic analysis of the dynamics, some important systems should be comprehensively modelled. Figure 5 provides a generic outlook of the important subsystems and their interaction in the simulation set-up for each vehicle. The environment model consists of all the external factors that affect the vehicle. Disturbances like wind gusts and wake from the aircraft are also included here. Since the RLV and capturing device remain behind the aircraft during IAC, they are very likely to be exposed to the wake disturbances some time during the trajectory.

Next, the vehicle model consists of inherent properties of the vehicle. The aerodynamics being one of the most critical subsystems, is calculated using high fidelity CFD simulations. A detailed study of aerodynamic characterisation of each vehicle is given in [11]. The propulsion module mainly consists of an engine model for the aircraft (since both RLV and capturing device are unpowered). And finally, the gravity block contains the mass and inertia properties. The dynamics block consists of the 6DOF equations of motion derived from Newton's laws [8],[12]. While plant model for each vehicle remains the same, the guidance and control algorithms change for different phases of IAC. Detailed modelling of all subsystems, including the flight controllers used for the simulations can be found in [8], [14] and [13].

3.2. Results

Prior to the IAC maneuver, the RLV re-enters the atmosphere and slows down through aerodynamic braking. Once the RLV stage is close to the aircraft, the IAC process begins. The first phase starts when both the vehicles try to follow a constant glide path with similar velocities, flying close to each other. During this, the capturing device is released from the TA and phase 2 commences. Once the capture has been established, the vehicles climb to a suitable cruise altitude (phase 3) and fly back to launch site.

For the *formation flight phase (phase 1)*, some requirements are defined for a successful formation. The formation must occur between an altitude of 3000 m and 8000 m. The RLV should remain behind the aircraft within a relative distance of 350 m. Lastly, the relative altitude should remain within ± 150 m and the relative velocity within ± 3.5 m/s. Figure 6 shows the altitude, velocity and relative distance during the gliding flight of the two vehicles. The green shaded region indicates the area in which the formation was successful. It was found that a formation could be held for up to 70 s. When the wake disturbances are taken into account, the formation flight duration reduces to 60 s (since the RLV position is perturbed by the wake). Although 60 s is sufficient time for the capturing device to connect the two vehicles, longer duration is recommended to allow for multiple attempts and redundancy. In the next steps, methods to extend the formation time will be explored.

In the *capture phase (phase 2)*, the capturing device attached by rope to the TA, attempts to reach the RLV while the formation is maintained. In the current study, a simplified trajectory simulation is performed. The maneuverability of capturing device is studied assuming the aircraft is in a steady flight at 6000 m. A flexible multibody rope model is included in the simulation to account for the disturbances due to flexibility. Based on some previous sensitivity studies, a 150 m long and 16 mm diameter rope made of material UHMWPE (Ultra High Molecular Weight Polyethylene) [14] is considered. As explained previously, the capturing device is controlled using the four aerodynamic flaps that can deflect up to ±15°. The goal is to achieve multiple maneuvers despite the vibrations from the rope. Figure 7 shows the relative position of the capturing device behind the aircraft. The capturing device is commanded to perform three

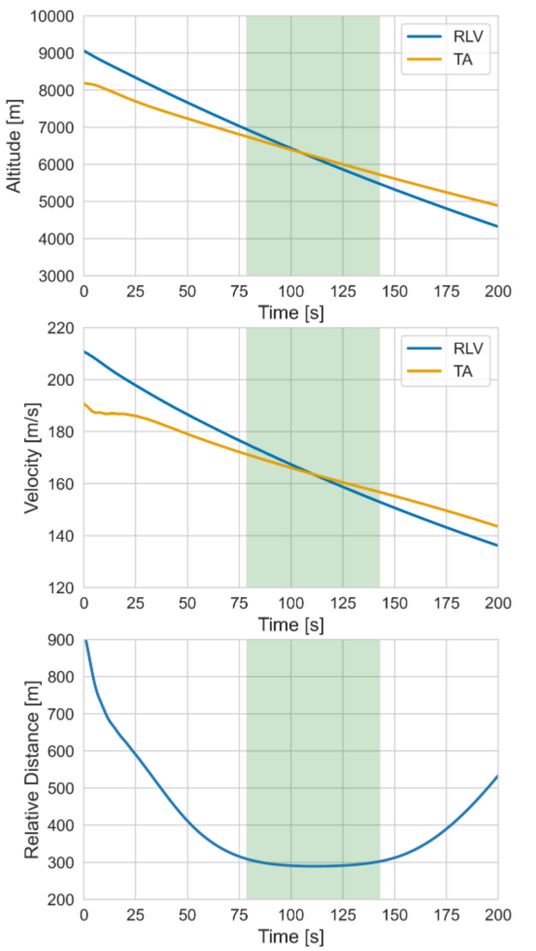

Figure 6: Formation Flight Trajectory between RLV and TA

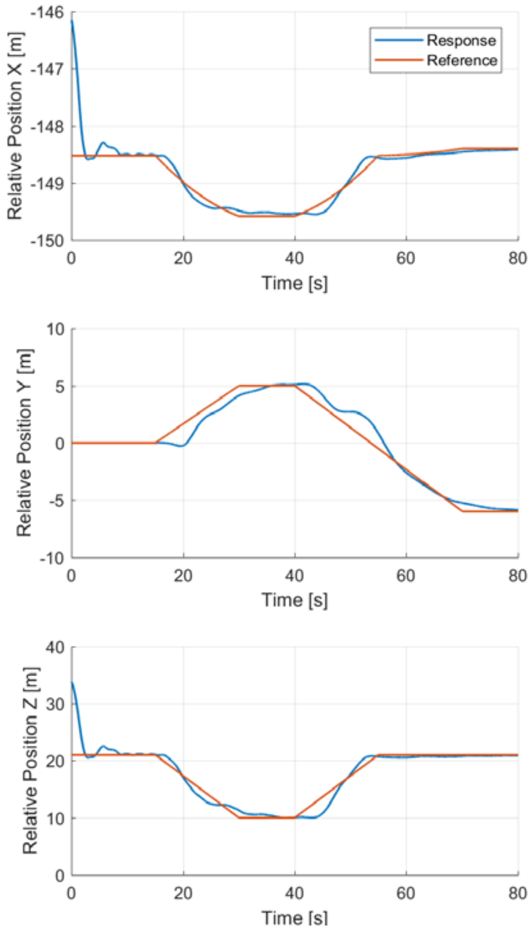

Figure 7: Controlled Response of Capturing Device Position

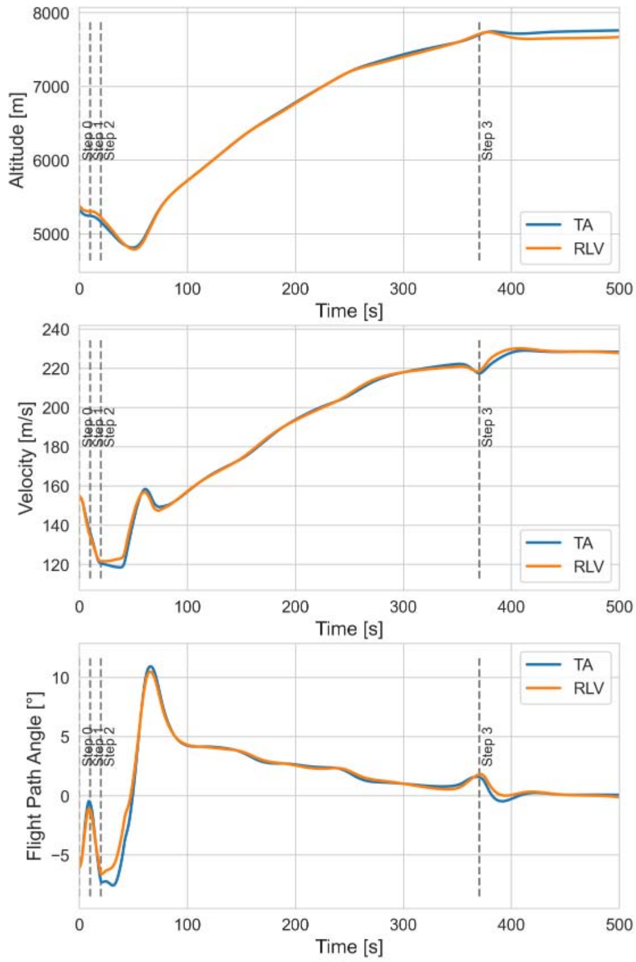

Figure 8: Pull-Up Maneuver Trajectory

maneuvers spanning up to 10 m in YZ direction. As it can be observed, the device was able to follow the commands and remained stable despite the vibrations from the rope. However, when the effect of wake was included, the device could not be controlled. Future work will include development of guidance schemes to attempt capture outside the wake of the aircraft. Further, the capture will be attempted with the TA and RLV in descent flight instead to constant altitude.

Assuming that the two vehicles are connected by the rope, the third phase can be examined. The simulations performed for *pull-up maneuver (phase 3)* assumes that the rope connecting the TA to RLV is a rigid link (150 m length). The goal of the simulations is to determine if the propulsion capacity of the TA is sufficient to pull the mated configuration to cruise altitude. Figure 8 shows the altitude, velocity and flight path angle (FPA) of the connected RLV and TA attempting *pull-up maneuver*. The simulation also takes in to account that the TA engines are throttled up to full capacity (step 1). Then, the two vehicles climb up to a cruise altitude (step 2) and finally, maintain constant altitude for the flight back (step 3). The configuration was successfully able to pull up to an altitude of about 7600 m and a velocity of 230 m/s. In future work, a flexible model of the rope will be included to analyze the associated challenges more realistically.

4. Conclusion

Within FALCon, an innovative launcher recovery mode called 'In-Air Capturing' was studied in international cooperation. One of the main goals of the project was to perform dynamic simulations with full-scale test cases to study and identify challenges of 'In-Air Capturing'. Full-scale test cases were first chosen for the reusable launch vehicle, the towing aircraft and the capturing device involved in the method. The simulation studies were divided into different phases to study the complex maneuvers in detail. Special focus was given to the first three phase - formation flight, capture phase and pull-up maneuver in the study. From preliminary simulations, the challenges and feasibility of the method were analyzed. Further, improvements and next steps for future simulations were also determined. Although all phases of the mission were studied separately to get a close understanding of dynamics, future studies would include a complete end-to-end simulation with optimized trajectories.

Acknowledgments

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