JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 42, No. 3, May–June 2005

Engineering Notes

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Air-Launching Earth to Orbit: Effects of Launch Conditions and Vehicle Aerodynamics

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Introduction

THE purpose of this study is to determine the benefits of air-launching expendable or reusable launch vehicles (LV) by using quantitative methods. Air-launch vehicles consist of at least two stages, a carrier aircraft and a rocket-powered LV. The carrier aircraft can be either subsonic or supersonic capable and can even include balloons. Air launch is one of the leading concepts that can meet today's launch requirements of both responsive and low cost. Previous work in this area has identified nonquantitative benefits and drawbacks of air-launch methods.[1] In this Note, many different air-launch scenarios associated with different release, launch conditions, and vehicle aerodynamics are modeled and simulated using trajectory optimizations. The trajectory optimization is conducted using POST, a numerical integration program based on the three-degree-of-freedom equations of motion of a flight vehicle.[2] More than 160 simulations were conducted in which launch altitude, speed, and flight-path angle were varied, and the effect of adding a wing was also modeled.

Velocity Budget to Reach Low Earth Orbit Using Air Launch

A LV must provide a change of velocity, ΔV or delta-V, in order to deliver a payload to low Earth orbit (LEO). The delta V from the LV's propulsion system depends on the time histories of the vacuum thrust and the mass of the LV. ΔV_{ideal} from the LV's propulsion system must equal the ΔV_{ideal} required for an earth to orbit trajectory as follows:

$$\Delta V_{\text{ideal}} = V_{\text{orbit}} + \Delta V_{\text{drag}} + \Delta V_{\text{gravity}} + \Delta V_{\text{steering}} + \Delta V_{\text{atmosphere pressure}} - V_{\text{earth rotation}} - V_{\text{carrier-aircraft}} \tag{1}$$

Presented as Paper 2004-872 at the AIAA 42nd Aerospace Sciences Meeting, Reno, NV, 5–8 January 2004; received 27 February 2004; revision received 26 November 2004; accepted for publication 13 December 2004.

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The orbit V_{orbit} and Earth rotation $V_{\text{earth-rotation}}$ velocities are driven by the satellite requirements, whereas the losses ΔV_{drag}, $\Delta V_{\text{gravity}}$, $\Delta V_{\text{steering}}$, $\Delta V_{\text{atmosphere-pressure}}$ are driven by the trajectory that connects the launch point to the orbit. The carrier aircraft's flight velocity at separation $V_{\text{carrier-aircraft}}$ is a function of the carrier aircraft capabilities and the release conditions. The change in velocity caused by Coriolis acceleration is ignored in Eq. (1) because its magnitude is very small, less than 10 m/s. Also, winds are assumed to be zero at all altitudes.

The first component V_{orbit} is the payload orbital velocity, and it depends on the altitude of the perigee and apogee of the orbit. The second component, drag losses ΔV_{drag} are caused by friction between the launch vehicle and the atmosphere and are on the order of 40–160 m/s for medium-sized launch vehicles such as Delta or Atlas rockets for a ground-launched Earth-to-orbit trajectory. Gravity losses $\Delta V_{\text{gravity}}$ arise because part of the rocket engine's energy is wasted holding the vehicle against the pull of Earth's gravity. They are highly dependent on the thrust-to-weight (T/W) ratio and are on the order of 1150–1600 m/s for ground-launch vehicles. Steering losses $\Delta V_{\text{steering}}$ are caused by the need to steer the LV. Atmospheric pressure losses $\Delta V_{\text{atmosphere-pressure}}$ are the difference in performance of a rocket motor in a vacuum as compared to its operation in the atmosphere. The best performance a rocket motor can provide is in a vacuum. Rocket thrust is calculated from the momentum change of the fuel and the difference in pressure at the nozzle exit. Any ambient pressure reduces the thrust of the rocket motor in the amount of atmospheric losses. Air launching always reduces atmospheric pressure losses because ambient pressure is lower at altitude as compared to sea level. The Earth rotation velocity increment $V_{\text{earth-rotation}}$ depends on launch latitude and launch direction. Finally, the carrier aircraft's flight speed $V_{\text{carrier-aircraft}}$ directly reduces delta V required from the launch-vehicle's propulsion system. However the benefit from the carrier aircraft's flight speed is highly dependent on both the T/W ratio at release and the flight-path angle that is the angle between the launch-vehicle velocity vector and the local horizontal.

Launch Conditions and Vehicle Aerodynamics

We used an existing launch vehicle, the Minotaur LV, so that we could check our numerical results with actual flight data. With the exception of its aerodynamic data, its characteristics are published. We simulated air launching the Minotaur over a range of altitudes, launch speeds, and launch flight-path angles. The altitudes chosen are sea level through 30,490 m at every 7620 m. The velocities are Mach 0, 1, 2, and 3, taken at sea level. The launch velocities were pushed just beyond current state-of-the-art speed of Mach 3 in order to capture some of the current proposed methods of launch. The sea-level Mach numbers are converted to equivalent velocities in the reported results. The launch flight-path angles are from horizontal to vertical, incremented at every 30 deg. Each launch condition was simulated with and without a wing. More than 160 simulations were conducted in which launch altitude, speed, and flight-path angle were varied, and the effect of adding a wing was also modeled. The Minotaur is a small 36,200-kg four-stage solid rocket that is currently ground launched. It consists of the first two stages of the Minuteman II and the upper two stages of the Pegasus XL. The Minotaur was also selected in our study because its initial T/W ratio was relatively high at 2.3 to 1, which is desired for an air-launch LV to reduce losses.

Three methods were used in determining the accuracy and sensitivity of the aerodynamic data. The payload performance, payload sensitivity, and velocity losses are all evaluated and compared to published values. The vehicle payload performance is evaluated by comparing two different launch simulations to the published values. The two launches were a 400 n mile sun-synchronous orbit from California and a 100 n mile 28.5-deg circular orbit from Florida. Both launches give a performance measure for comparison with the simulations. The simulation payload performance was very close to the published values with the percentage differences are at +5.6 and −0.67% respectively. The payload sensitivity was evaluated via varying the drag coefficients and running the POST simulation to find the resulting payload. Because drag data were not published, estimates were obtained from Datcom program.[3] Payload only changed by ± 8% when drag coefficients were varied from 25 to 200%. Hence, the drag values computed by the Datcom are acceptable. The velocity losses compare favorably with the published historic values.[4]

Discussion of Numerical Results

We report the benefits of air launch in terms of change in velocity. Delta-velocity gain ΔV_{gain} was obtained by taking the difference between the delta V calculated by POST for a ground launch from Cape Canaveral $\Delta V_{\text{ground-launch}}$ to a 185-km 28.5-deg inclination circular orbit and the delta V for an air launch $\Delta V_{\text{air-launch}}$ from the same location to the same orbit. Trajectory optimization program calculated that the reference ground launch orbit had a delta-V budget of 8918 m/s. The Minatour launch can place 646 kg in the orbit from Florida with total losses of 1534 m/s. Equation (2) compares the losses from the air launches to the ground launch. Thus, a positive

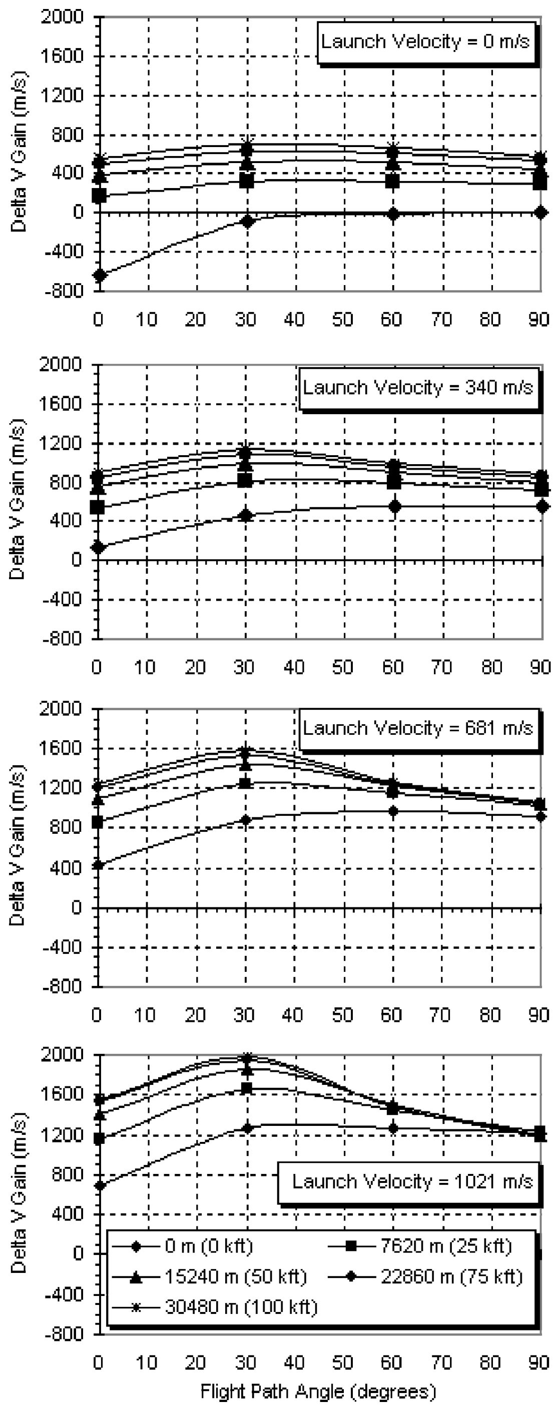

Fig. 1a Delta-V gain (no wing).

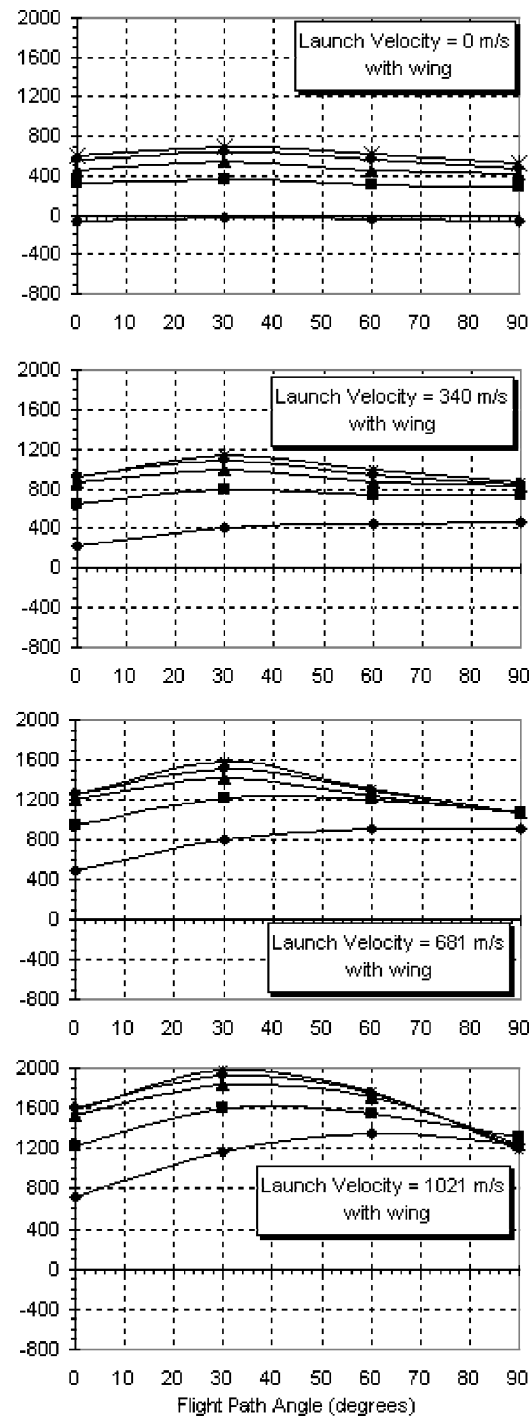

Fig. 1b Delta-V gain (wing for pull up).

delta-V gain from air launching is an improvement as compared to the ground launch:

$$\Delta V_{\text{gain}} = \Delta V_{\text{ground launch}} - \Delta V_{\text{air launch}} \tag{2}$$

In the simulation, we did not increase the size of the Minotaur's first-stage nozzles for higher altitude launches. The Minotaur first stage has four nozzles, each with an expansion ratio of 10 to 1. Using a larger nozzle expansion ratio for the higher altitude air launches would have resulted in an improved specific impulse. We kept the nozzles at 10 to 1 because those are approximately the largest nozzles that can physically fit on the back end of the Minotaur first stage. In addition, an idealized wing design was assumed with a mass of 12.2 kg/m^2. Although this is a typical area weight for a general aviation aircraft wing, fighter and transport aircraft wings weigh about four times this amount. Wing loading was assumed at a very high value of 1500 kg/m^2. In the simulation, the wing only assists the LV in turning to the proper flight-path angle and then is discarded. By assuming such a low weight for the wing, we are assuming a somewhat "best-case" scenario for a winged launch.

The Minatour structures were not modified. The designed structures were assumed to be capable of withstanding the forces encountered. The assumption that the original structures are adequate is the simplest method and avoids a full iterative design for each of the 80 air-launch points. It must be remembered that the added weight to survive certain launch conditions will reduce the performance. Three parameters were identified in order to capture all variations of the launch and release conditions. The altitude is the most recognized parameter of air launch, followed by the speed of the vehicle at motor ignition, and the climb angle is the last. All three parameters combine to yield a specific launch condition, and some corresponds to specific release conditions.

The ΔV_{gain} results are organized into two sets of plots shown in Figs. 1a (no wing) and 1b (wing for pull up). Positive values on the vertical axis indicate an improvement in ΔV_{gain}, and negative, a reduction in performance. The horizontal axis is the LV's flight-path angle at engine ignition. The LV flight-path angle at ignition will normally be less than the carrier aircraft flight-path angle because the LV engines are typically started some time after release for the safety of the carrier aircraft. Also the LV's altitude and airspeed will be typically less than the carrier aircraft's. Both Figs. 1a and 1b are based on LV flight-path angle, airspeed, and altitude at engine ignition and not on the carrier aircraft's parameters at LV release. Also the LV's body axis is aligned with the LV's velocity vector at engine start.

Altitude

Several trends are readily seen on these plots. All of the plots show that an increase in altitude increases ΔV_{gain}. The primary reason for the increase is the thinning atmosphere. At an altitude of 12,000 m, for example, the air density is 25% of the standard sea-level value. The lower atmospheric density decreases the drag, while the lower atmospheric pressure decreases the atmospheric thrust (pressure) losses. The greater thrust that a rocket engine provides at altitude allows the vehicle to accelerate faster, which in turn decreases the time that the vehicle is steering and fighting gravity. Hence all four major losses decreased with an air launch. There is very little improvement above 15,240 m.

Flight-Path Angle

The optimum flight-path angle for best ΔV_{gain} spans a range of about ± 15 deg because the curves in Figs. 1a and 1b are relatively flat near their peaks. Adding a wing reduces the optimum flight-path angle for maximum ΔV_{gain} at low angles and low carrier aircraft speeds. The optimal launch angle is different for each launch condition. The optimal flight-path angle can best be described as the trajectory with the least maneuvering. Pull ups and other sudden maneuvers increase steering and drag losses. Air launches at a low initial flight-path angle and at a low altitude cause the LV to pull up in order to fly the optimum trajectory to orbit. This pull-up causes increased losses. At high altitudes, too steep of an initial flight-path angle results in the LV pitching down in order to fly the optimum trajectory. Pitching down increases the losses. A minimum flight path of 30 deg above the horizontal at ignition can be used for a first approximation to maximize ΔV_{gain}. A release attitude of less than 30 deg might require a wing.

Wings

The addition of a wing has advantages and disadvantages. The advantage of a wing is the aerodynamic lift it can provide. The disadvantages are the induced drag it produces and its weight. The wing provides the ability to turn more efficiently, but it only provides benefits at launch when the launch angle is near the horizontal.

In an expendable launch vehicle (ELV), to maximize the effectiveness of the wing it should be used only for the initial pull-up maneuver and then immediately jettisoned to reduce weight. The wing reduces the angle of attack required to complete a pull-up maneuver, which in turn reduces drag. Without the wing, the turn is completed by using engine thrust while the rocket's body briefly generates large amounts of drag. In an RLV, the wing can provide further benefits later in the trajectory by reducing gravity losses at the expense of increased drag losses. A winged RLV can fly a lifting trajectory that allows it to pitch over to the horizontal earlier.

If the carrier aircraft releases an ELV at a flight-path angle that is close to the optimum shown in Fig. 1a, then the wing provides no ΔV_{gain}. If the carrier aircraft cannot pull up to the optimum flight-path angle, then a wing can help. However, placing a wingless LV onto the optimal flight-path angle with the carrier aircraft achieves slightly higher ΔV_{gain} as compared to a winged LV caused by eliminating the wing's weight and drag. As always, weight is an aeroengineer's enemy.

Velocity

The carrier aircraft's flight speed $V_{\text{carrier-aircraft}}$ improves V_{gain}. The ΔV_{gain} from air launching can exceed the contribution made by the carrier aircraft's flight speed or the carrier aircraft's flight speed might not even provide a one to one benefit toward ΔV_{gain}. The magnitude of the benefit depends on the LV's flight-path angle at engine start. For example, examine Fig. 1a and consider a 340-m/s (Mach 1) launch at a 60-deg flight-path angle at a sea-level altitude. Although this is an unrealistic launch condition, note that the V_{gain} is 560 m/s. The gain comes from both the initial launch velocity (340 m/s) and a change in the losses. In this case, the high velocity near the ground will increase drag losses, but the same conditions decrease gravity and steering losses even more. On the other hand, reducing the flight-path angle to 0 deg for the same altitude and airspeed reduces ΔV_{gain} to 130 m/s, which is less than $V_{\text{carrier-aircraft}}$. In this case additional drag and steering losses overwhelm both the improvement in gravity losses and the carrier aircraft's flight speed contribution. This example illustrates the complex interplay between the losses and the importance of launching near the optimum flight-path angle.

Conclusions

Based on this parametric study, the most beneficial carrier aircraft launch parameters are in the following order: launch velocity, launch flight-path angle, and launch altitude. In addition, there is an optimum launch flight-path angle that maximizes the velocity benefit from air launching. A minimum of 30 deg above the horizontal can be used as a first approximation for flight-path angle at ignition for maximum velocity benefit. Once above about 15,000 ms, added launch altitude had little additional benefit.

Although this was a comparative study involving only one launch vehicle and one reference orbit, we believe that the data presented in this Note can play a useful role in the future conceptual design of air-launched expendable and reusable launch vehicles. Many questions can be answered. For example, should an air launch occur at the service ceiling of the carrier aircraft in straight-and-level flight, or should the launch occur at a lower altitude with the carrier aircraft in a zoom climb? If a zoom climb is used, when should the launch vehicle (LV) be released, at the start of the climb or at the apogee? Should the LV have wings or not? Knowledge of the carrier aircraft's capabilities together with the data in Figs. 1a and 1b can provide preliminary answers to these and other questions.

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