Beaming Flight of Repetitive-Pulse Powered Vehicle for Satellite Launch

By Masayuki TAKAHASHI and Naofumi OHNISHI
Department of Aerospace Engineering, Tohoku University, Sendai, Japan

(Received June 24th, 2013)

To present a feasibility of high-altitude flight of a laser-propelled vehicle at supersonic speed, we have developed a flight simulator which has fluid-orbit coupling calculation module to reproduce impulsive flight reaction driven by blast waves. By high-power energy transmission through arrayed lasers together with the genetic algorithm (GA) controlled sub-laser, the supersonic flight is successfully achieved in the simulation for 32.5-g vehicle, while the angular offset should be suppressed as small as possible. Rather than translational position, controlling angular offsets by the GA operation is especially important to attain the km-order flight on the premise of the active control. Additionally, the vehicle weight, the vehicle size, and the input energy are scaled up to assess the stable flight of 10-kg vehicle. The active control technique has enough possibility to launch kg-order vehicle at supersonic regime with the optimized beaming strategy.

Key Words: Beam-Riding Flight, Blast Wave, Computational Fluid Dynamics, Genetics Algorithm

Nomenclature

- \( C \) : aerodynamic coefficient
- \( \mathbf{E}, \mathbf{F}, \mathbf{G} \) : flux vectors in \( x-, y-, z- \) directions
- \( \mathbf{\dot{E}}, \mathbf{\dot{F}}, \mathbf{\dot{G}} \) : viscous flux vectors in \( x-, y-, z- \) directions
- \( I \) : moment of inertia or impulse
- \( k \) : impulse scaling factor
- \( m \) : vehicle mass
- \( M, L, N \) : external moments in body-fixed coordinate
- \( P, Q, R \) : angular velocities in body-fixed coordinate
- \( \mathbf{Q} \) : conservative vector
- \( r \) : distance vector in flowfield
- \( t \) : time
- \( u \) : flow velocity vector
- \( U, V, W \) : vehicle velocities in body-fixed coordinate
- \( \mathbf{U} \) : translational velocity vector
- \( w \) : beam radius
- \( x, y, z \) : flowfield coordinates
- \( X, Y, Z \) : external forces in body-fixed coordinate
- \( \Delta U \) : variation of translational velocity
- \( \Delta \Omega \) : variation of angular velocity
- \( \mathbf{\Omega} \) : angular velocity vector
- \( \Pi \) : evaluation function
- \( \rho \) : ambient density
- \( \zeta \) : angle of attack

Subscripts

- \( \theta \) : reference value
- \( a \) : aerodynamics or angular motion
- \( c \) : computational cell in flowfield or current
- \( d \) : drag
- \( E \) : earth-fixed coordinate
- \( g \) : gravity and center of gravity
- \( l \) : lift
- \( m \) : moment

1. Introduction

Launches of small-sized satellite are typically conducted by rockets for shared-ride piggyback transportation together with a main satellite. However, in recent years, a compact launching scheme at university level is needed for atmospheric observation, weightlessness experiments, and other academic studies. Because the launch timing is strictly restricted by the main satellite in the shared-ride system, activation of academic use is impeded, and so it is necessary to establish the exclusive and flexible launch system for small satellites at a lower cost. Laser propulsion rocket which has possibility to minimize fuel equipped on the vehicle is expected as a novel launcher with the cost-cutting, while the propulsion energy is transmitted from a ground base in the form of a directional laser beam. An aero-driving laser vehicle obtains thrust through interactions with a blast wave induced by repetitive pulses from the ground base. The blast wave can propel the vehicle to a higher altitude; however, if the vehicle cannot capture the laser beam, no thrust is obtained and the flight fails to continue. Flight performance to successively capture the incident beam, called beam riding performance, is crucial for the vehicle to receive continuous thrust. The beam riding performance is assessed by the centering and tipping performances against incident misalignments in the lateral and angular directions.

One of the best beam riding vehicles is the “lightcraft” proposed by Myrabo, and the type-200 spinning lightcraft achieved a 71-m altitude flight in 2001. The lightcraft is constructed from forward body, ring shroud, and rear body with the parabolic mirror. The blast wave interacts with the shroud of the lightcraft, which can generate centering-feedback force against the lateral offset of the laser incident. Axial high speed spin is also added to induce a precessional
motion for tilting stabilization. In past studies of the lightcraft, some experiments were conducted to examine recentering and angular impulses only for the lateral offset with a single pulse \(^5,7\). Also, flight simulations were performed with multiple laser pulses based on the impulse data for the lateral offsets \(^8,9\). However, the deviation mechanism from the laser beam line was not specified from the past studies because the angular offset and angular-lateral combined offset were not introduced.

In our previous work \(^10,11\), we have developed a fluid-orbit coupling calculation code with a ray-tracing to reproduce the incident offsets during the flight. For a single pulse, data-maps of vehicle reactions against the lateral, angular, and these combination offsets have been made to save the computational load for the flight calculation with multiple pulses. The flight calculation with the multiple pulses was successfully reproduced using the data-maps, and we found that the growth of the angular offset causes the deviation from the laser beam line. Based on the obtained flight dynamics we proposed an active control concept using a genetic algorithm (GA) to achieve a higher flight altitude. The flight can be maintained in km-order altitude if the angular offset is suppressed in a smaller size by the optimized position control for the laser irradiation. However, the stable flight of only 32.5-g weight vehicle was examined using the active control, and so it is necessary to scale up the vehicle weight, the vehicle size, and the input power.

The objective of the present study is demonstrating the supersonic flight of the kg-order mass vehicle by introducing the active control technique. A bunch of lasers is irradiated as the arrayed lasers with keeping the parallel axes to the vehicle’s one to transmit the high power beam for accelerating the vehicle into the supersonic speed. In this study, instead of irradiating spatially arranged lasers at the same timing, the several single lasers are dispersively irradiated at different timings during the pulse interval. In addition, the GA controlled single laser is irradiated for suppressing the angular offset and maintaining the posture stability during the multiple-pulse flight (Fig. 1).

2. Numerical Methods

2.1. Simulation flowcharts

The flowfield calculation is coupled with an orbital calculation for assessing a flight reaction driven by the blast wave. Without the serious three-dimensional fluid simulation, the multiple-pulse simulation is conducted using the steady aerodynamic coefficients and the impulse data-maps to save the computational load. The impulse data-maps are constructed by the fluid-orbit coupling calculation for the beaming parameters of the lateral, angular, and lateral-angular combination offsets. Figure 2 shows two flowcharts for the construction of the impulse data-maps and the multiple-pulse simulation using the data-maps.

Fig. 2. Flowcharts for data-map construction and multiple-pulse flight.

2.2. Flowfield calculation

The flowfield around a spinning lightcraft is to be obtained for estimation of forces and moments acting on the vehicle. An unsteady flowfield involving a blast wave propagation is predicted by computational fluid dynamics (CFD). The three-dimensional Navier-Stokes equation is numerically solved to reproduce the compressible gas dynamics around the vehicle:

\[
\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial (\mathbf{E} - \mathbf{E})}{\partial x} + \frac{\partial (\mathbf{F} - \mathbf{F})}{\partial y} + \frac{\partial (\mathbf{G} - \mathbf{G})}{\partial z} = 0. \quad (1)
\]

Discretization is performed by the cell-centered finite volume manner. The AUSM-DV method \(^12\) is employed for numerical flux with the second-order MUSCL method \(^13\). The viscous flux is estimated by the second-order central difference method, and the viscous coefficient is estimated by Sutherland’s formula. The Spalart-Allmaras model \(^14\) with an assumption of fully developed turbulence due to the axial spin of the lightcraft is employed to introduce the effect of the turbulent flow. The LU-SSOR method \(^15,16\) is utilized for the time integration of steady flow problems (e.g., measurements of aerodynamic coefficients) to save the computational time. Time integration for unsteady flows is performed by the first-order explicit Euler method. In an early stage of the blast wave propagation, we couple the flowfield calculation with the orbital one to introduce the effects of the instantaneously driven vehicle motion. The fluid calculation code is vectorized and parallelized for a computing speed-up.

It is necessary to obtain the rotating flow around the lightcraft before the blast wave simulation because the lightcraft has the
initial high-speed spin of 10000 rpm for a gyro stabilization.\(^9\)

After we obtain the steady solution around the axially spinning lightcraft using the LU-SSOR method, the ray-tracing method\(^17\) is carried out to deposit an energy source for the blast wave. The deposited energy distribution depending on the lateral, angular, and lateral-angular offsets is assessed by tracing the laser beam numerically divided into hundreds of rays. The 420-J\(^9\) and 140000-J laser beam with 26-Hz repetition frequency are irradiated to the 32.5-g\(^9\) and 10-kg vehicle, respectively. The efficiency of laser energy absorption by plasma is assumed to be 60% so as to adjust the generated impulse to the experimental impulse data.\(^9\)

### 2.3. Flight trajectory calculation

An flight orbit of the vehicle can be calculated by six-degree-of-freedom (6-DOF) equations of motion with aerodynamic forces and moments estimated from a flowfield solution. The 6-DOF equations of motion for the trajectory estimation are given by

\[
m(U + QW - RV) = X_g + X_a,
\]
\[
m(V + RU - PW) = Y_g + Y_a,
\]
\[
m(W + PV - QU) = Z_g + Z_a,
\]
\[
I_{zz}P + (I_{zz} - I_{yy})QR = I_g + I_a,
\]
\[
I_{yy}Q + (I_{zz} - I_{xx})RP = M_g + M_a,
\]
\[
I_{zz}R + (I_{yy} - I_{xx})PQ = N_g + N_a.
\]

The aerodynamic forces, moments, gravity forces, and gravity gradient torques\(^10\) are introduced as the external forces and moments acting on the vehicle. When the blast wave strongly interacts with the vehicle surface, the aerodynamic forces and moments are estimated by integrating surface pressure distribution obtained by the flowfield solution. If the interaction between the blast wave and the vehicle can be ignored, only the 6-DOF equations of motion are integrated using the aerodynamic coefficients for the steady flow. The time integration is conducted by the 4th-order Runge-Kutta method.

### 2.4. Fluid-orbit coupling calculation

Because the vehicle is instantaneously driven by the strong blast wave in the early stage of the blast wave propagation, we must introduce the effect of vehicle motion on the flowfield. The flowfield computation and the 6-DOF orbital calculation are combined to model the effect of rapid flight motion in the body-fixed coordinate system. The time variations of the vehicle velocities and angular velocities are fed back to the flowfield calculation at each step as follows;

The flowfield-orbital coupling calculation is conducted\(^9\)

\[
u_{ref} = u - \Delta U - \Delta \Omega \times (\mathbf{r}_e - \mathbf{r}_f).
\]

until the forces from the blast wave can be ignored. Because the positive and negative pressures of the blast wave completely pass through the vehicle surface and the obtained thrust becomes 0 before 1000 \(\mu\)s, the fluid-orbit coupling simulation is terminated at 1000 \(\mu\)s. The negative thrust by the expansion region of the blast wave is included in this calculation, but the net impulse becomes positive.

For the time interval in which the interaction between the blast wave can be ignored, we integrate only the 6-DOF equations of motion with the external forces and moments derived from the aerodynamic coefficients of the non-spinning lightcraft. In subsonic flow, the aerodynamic coefficients of the non-spinning lightcraft are approximated by the following forms\(^9\);

\[
C_d = 0.3928\zeta^4 - 0.8463\zeta^3 + 0.0398\zeta + 0.731,
\]
\[
C_I = 0.1993\zeta^4 - 0.3317\zeta^3 - 0.5351\zeta^2 - 0.0316\zeta,
\]
\[
C_m = 0.1598\zeta^4 - 0.6619\zeta^3 + 0.8794\zeta^2 - 0.3585\zeta^3 - 0.0583\zeta^2 + 0.080\zeta.
\]

In the supersonic flight, the aerodynamic coefficients are estimated by our CFD code and incorporated into the 6-DOF orbital calculation. The aerodynamic loads increase due to a wave drag in the supersonic flight compared with those in the subsonic speed. The aerodynamic coefficients are assessed for the angle of attacks of 0, 0.2, 0.4, 0.6, and 0.8 rads at the flight Mach number of 1.25 (Fig. 3). Because the aerodynamic coefficients become smaller with Mach number increasing for more than Mach 1.25\(^1\), the aerodynamic coefficients are overestimated for higher Mach number in this calculation.

2.5. Motion data-maps and multiple-pulse simulation

The data-maps of impulsive vehicle motion are used to reduce the computational load for the multiple-pulse simulation\(^10\). The data-maps are constructed for the lateral, angular, and lateral-angular combination offsets at the reference altitude of 1.194 km\(^9\) through the fluid-orbit coupling calculation. In the multiple-pulse simulation, the impulse by the blast wave is linearly interpolated from the data-maps at the pulse incidence timing. After the pulse incidence, the 6-DOF equations of motion is temporally integrated with the steady aerodynamic coefficients until the next pulse.

Because the data-maps were made for the 32.5-g vehicle with the 420-J laser in our previous work\(^9\), the data-maps should be scaled up for the 10-kg vehicle simulation with larger energy input. The dynamical equivalent should be maintained in a scaled-up calculation for obtaining the stable flight of the 10-kg vehicle with a similar fashion of the 32.5-g flight. When the aerodynamic drag effect is ignored, the laser energy of one pulse is adjusted to 140,000 J for 10-kg vehicle to maintain a dynamical equivalent against the 32.5-g case in the translational direction. Depending on the vehicle weight increment, the vehicle size and the moment of inertia are enlarged with...
keeping the vehicle mass density and the similarity of the vehicle geometry. We actually confirm the dynamical equivalent by the numerical simulation for the 10-kg vehicle using the 140,000-J laser. For the translational motion of the 10-kg vehicle, we can use the almost same impulse data-maps of the 32.5-g case because the dynamical equivalent is successfully kept. However, we correct the data-maps for the angular direction because the dynamical equivalent is not maintained in the angular direction. We multiply the data of the angular impulse by a correction factor \((0.1535)\) to maintain the dynamical equivalence for the angular motion.

In the multiple-pulse flight calculation, the ambient density is given by the US standard atmosphere 1976 model. The multiple-pulse calculation is terminated if the vehicle falls or the vehicle achieves 86-km altitude which is the limit of the atmosphere model. Because the generated impulse depends on the beam divergence and the ambient density, it is necessary to correct the impulse data-maps for the reference altitude with increasing the flight altitude. The beam divergence is assessed by a theory of the Gaussian beam \(^{39}\) with a wavelength of 10.6 m. Thrust decay by density decrease and beam divergence with altitude is modeled based on the three-dimensional spherical Sedov solution \(^{39}\). By temporally and spatially integrating the shock pressure of the Sedov solution, the translational and angular accelerations by the blast wave are modeled as follows;

\[
U_E = U_{bE} + k_1 \left( \frac{\rho}{\rho_0} \right)^{1/2} \left( \frac{u_0}{w} \right) \Delta U_{b0},
\]

\[
\Omega_E = \Omega_{bE} + k_2 \left( \frac{\rho}{\rho_0} \right)^{1/2} \left( \frac{u_0}{w} \right) \Delta \Omega_{b0}.
\]

2.6. Laser position control using genetic algorithm

To maintain a stable flight and achieve a km-order altitude, the laser beam is actively controlled based on the optimization algorithm. We employ the real-coded genetic algorithm (GA) \(^{28}\) to determine laser incident position for keeping posture stability of the vehicle. In the real-coded GA, BLX-\(\alpha\) model \(^{21}\) is employed for a crossover. Minimal Generation Gap (MGG) model \(^{20}\) is used for a generation alternation while a mutation is not installed in this study. If the BLX-\(\alpha\) and MGG models are combined, we can maintain sufficient variety to avoid the locally optimized solution without the mutation.

The present GA procedure is as follows. At first, 100 laser position vectors are randomly created. Parents are selected from this group, and the BLX-\(\alpha\) is operated 100 times to generate 200 children. After that, using the MGG model, two individuals are selected from the group including the original parents and children. Lastly, the parents are replaced by these individuals. This process is repeated until the terminal condition is satisfied. When the evaluation function becomes sufficiently small or the GA iteration exceeds 100 times, the GA operation is terminated. For the optimization, the evaluation function \(\Pi\) is defined to the angular offset because the flight destabilization occurs by the growth of the angular offset. For estimating the evaluation function, the 6-DOF equations of motion are integrated for 200 laser position vectors at the pulse incident timing. The parallelization by the MPI library is conducted in the optimization module to save the computational time for the evaluation function.

3. Results

3.1. Attempt for supersonic flight using GA control

The initial lateral offset of the laser incidence is set to 5 mm in this calculation. The stable flight should be attained in supersonic speed when the high-power beam is irradiated into the vehicle from the ground base. In a realistic way for high-power energy transmission, the bunch of many lasers is irradiated to the vehicle. In this paper, the arrayed 90 lasers whose axes are paralleled to the vehicle axis are irradiated to the vehicle center for obtaining larger thrust and stable moments with the assumption that the single laser has the 420-J energy and 26-Hz frequency for the 32.5-g vehicle as used in the past flight experiment \(^{19}\). In addition, a sub-laser controlled by the GA is irradiated to suppress the angular offset and keep the posture stability. The sub-laser is actively controlled to minimize the angular offset by following the evaluation function \(\Pi\). Both the sub-laser and the arrayed lasers are moved, but moving approaches are different; the only sub-laser follows the optimization scheme, while the arrayed lasers are simply irradiated parallel to the vehicle axis. The 90 lasers are dispersively irradiated during the pulse interval to irradiate the bunch of many lasers.

The beam-riding flight is stably sustained in km-order flight altitude using the GA controlled sub-laser, while the translational position of the vehicle is successfully maintained in the vicinity of the starting point (Fig. 4). The vehicle can achieve 70-km flight altitude with keeping the stable flight, but can not advance for over 70-km altitude due to the density decrease. The angular offset is suppressed in small size of less than 0.001 degree by the GA optimization (Fig. 5). Suppressing the angular offset is especially important to achieve a km-order flight rather than the centering feedback based on the premise of the active flight control. A supersonic flight is achieved by the arrayed 90 lasers and sub-laser irradiations at 135 s (Fig. 6(a)). The vehicle velocity jumps when the sub-laser and one of the arrayed lasers are simultaneously irradiated into the vehicle (Fig. 6(b)). At the beginning, the vehicle velocity has oscillation during the pulse interval because a force of inertia is small due to the light vehicle weight. In high altitude, the oscillation vanishes because of the thrust and aerodynamic drag decreasing. However, at least kg-order weight vehicle may be used for an actual satellite launch; it is therefore necessary to scale up the vehicle size, the vehicle weight, and the input laser power.

Fig. 4. Flight trajectory for 32.5-g vehicle using arrayed 90 lasers.
3.2. Supersonic flight for 10-kg weight vehicle

With the initial offset of 5 mm, the flight simulation for a 10-kg weight vehicle is conducted using the arrayed 90 lasers constructed from the bunch of 140,000-J single beam. The laser energy of one pulse is adjusted to 140,000 J to keep the equivalent motion against the 32.5-g case in the translational direction. The GA controlled sub-laser is also irradiated for the posture control through the optimization scheme. The sub-laser has same power as the single pulse of the 140,000-J energy and 26-Hz frequency. For the single laser beam, the impulse data-maps are scaled up through the fluid-orbit computation for the 10-kg vehicle with 140,000-J single pulse. The scaled-up impulses are dispersively input during the pulse interval to irradiate the bunch of lasers. The total power for the 10-kg vehicle is 328 MW using the 26-Hz repetitive pulse, while the transmitted power is only 1 MW for the 32.5-g case.

For the 10-kg vehicle, the stable flight of the beam riding fashion is maintained using the arrayed lasers and the laser control technique (Fig. 7). The stable flight and the positive thrust are maintained for more than 70-km altitude due to the larger inertia, and the vehicle achieves the limit altitude of the atmosphere model. The supersonic flight is also achieved by the intense beam of the total power of 328 MW (Fig. 8). Actually, the dynamical equivalent is not maintained as compared with the 32.5-g case because the aerodynamic drag effect is ignored for the impulse scaling. The flight speed becomes larger than the 32.5-g case due to the larger inertia of the heavy weight during the free flight of the pulse interval. It is necessary to consider the effect of the aerodynamic drag in the impulse scaling.

If the beam power is simply increased, the active laser control has enough possibility to launch the kg-order vehicle. If the dynamical equivalence is successfully kept between the actual launch scale and the laboratory scale, the flight test in the laboratory size may show the flight feasibility of the actual scale with the higher power beam.

4. Conclusion

The arrayed lasers and the GA controlled sub-laser irradiation are assessed for achieving the supersonic flight with keeping the stable flight with the developed flight
simulator for the beam riding vehicle. Using the active laser control based on the GA operation whose evaluation function is defined by the angular offset, the stable flight can be achieved without deviation from the laser beam line. It is effective that the arrayed lasers and sub-laser for the posture control are simultaneously irradiated to achieve the supersonic speed with keeping the stable flight. If the laser beam power is increased, the active control can launch the 10-kg vehicle in the beam-riding strategy at supersonic regime.

Acknowledgements

The computations in this work were performed on NEC SX-9 model A and SGI Altix UV1000 at Advanced Fluid Information Research Center, Institute of Fluid Sciences, Tohoku University

References