Fluid-orbit coupling calculation for flight analysis of impulsively driven laser vehicle

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Abstract. Using a fluid-orbit coupling simulator, we numerically solve the three-dimensional Navier-Stokes equations with exchanging information of six-degree-of-freedom reactions for predicting impulsive flight motions of a laser propulsion vehicle driven by blast waves. By feedback of angular and translational velocities into the flowfield, pressure and viscous drags induced by the unsteady vehicle motion are introduced to provide precise motion analysis. In the impulsive-motion estimation of the laser-boosted vehicle, restoring forces and moments are underestimated if the vehicle motion effect is modeled using aerodynamic coefficients of steady flow. Also, a simple model using impulse data examined by experiments for predicting the impulsive motion is compared with our coupling approach which can reproduce instantaneous acceleration resulting from the interaction between the vehicle and the blast wave. Velocity overshoot is generated by evaluating sharp thrust through the coupling calculation, and the flight height becomes 6% larger than conventional prediction using the impulse data.

1. Introduction
For various purposes in science, business, and national security, many small artificial satellites are launched by a shared-ride piggyback transportation together with a main satellite [1]. However, the shared-ride system restricts the launch timing and injection orbit of the small satellite, and this is the main factor preventing easy planning of small- or middle-scale projects. Therefore, it is necessary to establish an exclusive launch system for small satellites at lower cost. Laser propulsion is a novel system for small-satellite launch. It saves fuel on the vehicle and increases the payload ratio [2–7]. In aero-driving type propulsion, the vehicle obtains thrust through interactions with a blast wave induced by repetitive laser pulse irradiated from a ground base. According to feasibility and cost studies of laser propulsion [8–10], launch cost can be reduced to a quarter of the present LOH/LH2 engine rocket by repaying the initial cost of the ground base through repetition launch of small-sized vehicles.

It is well known that the flight performance of the “lightcraft” proposed by Myrabo [3] is excellent among present laser propulsion vehicles. The interaction between the blast wave and a shroud of the lightcraft pushes the vehicle back toward the center of the laser beam if the incident laser has lateral misalignment against the vehicle axis, and so the lateral offset is reduced [11]. A type-200 spinning lightcraft of 50-g weight was launched and achieved 71-m altitude in 2001 [3].

In past studies of the lightcraft, some experiments were conducted to examine recentering and angular impulses for lateral offset with a single pulse [12, 13]. Also, flight simulations were performed with multiple pulses based on the impulse data for lateral offsets [11, 14]. In the modeling of the multiple-pulse flight, the vehicle velocity is incremented by adding the impulse...
data at the time of incidence of the pulse for simplicity of temporal integration of the time-dependent thrust, and the unsteady interactions with the strong blast wave are ignored in the motion analysis [11, 14]. However, the vehicle is rapidly accelerated during the unsteady interaction with shock waves; thus, a state-of-the-art flight analysis is required for more precise predictions of the vehicle motion using a fluid-orbit coupling approach.

Objective of the present study is analysing the unsteady motion of the lightcraft by a numerical code coupling with compressible hydrodynamics and flight orbit [15–17]. For the impulsive motion estimation, we compare the simple approach using impulse data with our coupling calculation which can reproduce the severe interaction between the vehicle and the blast wave.

2. Numerical Methods
Computational models for fluid-orbit coupling simulation are based on our previous papers [15–17], and we briefly introduce the numerical methods here.

2.1. Flowfield calculation
Flowfield around a spinning lightcraft is solved to estimate forces and moments acting on the vehicle. To predict an unsteady flowfield involving a laser-induced blast wave, the three-dimensional Navier-Stokes equations are numerically solved:

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial (\mathbf{E} - \mathbf{E}^1)}{\partial x} + \frac{\partial (\mathbf{F} - \mathbf{F}^1)}{\partial y} + \frac{\partial (\mathbf{G} - \mathbf{G}^1)}{\partial z} = 0,$$

where $\mathbf{Q}$ is the vector of conservative variables, $\mathbf{E}$, $\mathbf{F}$, and $\mathbf{G}$ are the inviscid flux vectors, and $\mathbf{E}^1$, $\mathbf{F}^1$, and $\mathbf{G}^1$ are the viscous flux vectors in the directions of $x$, $y$, and $z$, respectively.

Discretization is done through a cell-centered finite volume method. The AUSM-DV method [18] is employed for the numerical flux with the second-order MUSCL method [19]. The numerical flux is calculated with a local rotation matrix to introduce a general curvilinear coordinate [20,21]. In the MUSCL method, we choose the characteristic variables as interpolation quantities and use the minmod limiter to fulfill the TVD condition [19]. The viscous flux is estimated through a second-order central difference method, and the viscous coefficient is determined by Sutherland’s formula [22]. The Spalart-Allmaras model [23] 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. Time integration for unsteady flows is performed through first-order explicit Euler method.

2.2. Orbital calculation
A vehicle’s flight trajectory can be predicted by solving six-degree-of-freedom (6-DOF) equations of motion. The conservation of linear and angular momenta for a rigid body results in 6-DOF equations of motion expressed in the body-fixed coordinate system. The 6-DOF equations of motion for tracing the vehicle trajectory are given by

$$m(\dot{U} + QW - RV) = X_g + X_a,$$

$$m(\dot{V} + RU - PW) = Y_g + Y_a,$$

$$m(\dot{W} + PV - QU) = Z_g + Z_a,$$

$$I_{xx}\dot{P} + (I_{zz} - I_{yy})QR = L_g + L_a,$$

$$I_{yy}\dot{Q} + (I_{xx} - I_{zz})RP = M_g + M_a,$$

$$I_{zz}\dot{R} + (I_{yy} - I_{xx})PQ = N_g + N_a,$$
where $m$ is the mass of the vehicle, $U$, $V$, and $W$ are the velocities of the vehicle, $P$, $Q$, and $R$ are the angular velocities of the vehicle (Fig. 1), $X_g$, $Y_g$, and $Z_g$ are the gravity forces, $L_g$, $M_g$, and $N_g$ are the aerodynamic moments, $L_g$, $M_g$, and $N_g$ are the gravity gradient torques [24] in the body-fixed coordinate system $XYZ$, and $I_{xx}$, $I_{yy}$, and $I_{zz}$ are the moments of inertia for $X$-, $Y$-, and $Z$-directions, respectively.

When the blast wave interacts with the vehicle surface, the aerodynamic forces and the aerodynamic moments are estimated by integrating the surface pressure distribution and the viscous stress from the flowfield solution in the body-fixed coordinate system. We also introduce gravity forces and gravity gradient torques acting on the vehicle in addition to aerodynamic forces and moments. The gravity gradient torques generate the restoring moment because the distance between the center of the earth and each micro-element of the vehicle is different [24].

![Figure 1](image)

**Figure 1.** Definitions of Velocities and angular velocities in the body-fixed coordinate system $XYZ$ [15, 16].

### 2.3. Coupling method

Because the vehicle is instantaneously driven by the strong blast wave, we must introduce an effect of vehicle motion on the flowfield. We combine the flowfield and the orbital calculation to introduce the vehicle motion effect in the body-fixed coordinate system.

In the orbital calculation, the aerodynamic forces and moments are estimated by integrating the surface pressure distribution and the viscous stress from the flowfield solution in the body-fixed coordinate system. For the flowfield computation, the time variations of vehicle velocities $\Delta \mathbf{U} = [\Delta U, \Delta V, \Delta W]^T$ and angular velocities $\Delta \mathbf{\Omega} = [\Delta P, \Delta Q, \Delta R]^T$ are fed back to the flowfield calculation at each step except for an axial high speed spin:

$$\mathbf{u}_{\text{new}} = \mathbf{u} - \Delta \mathbf{U} - \Delta \mathbf{\Omega} \times (\mathbf{r}_c - \mathbf{r}_g),$$

where $\mathbf{u} = [u, v, w]^T$ is the flowfield velocity, $\mathbf{u}_{\text{new}} = [u_{\text{new}}, v_{\text{new}}, w_{\text{new}}]^T$ is new velocity of the flowfield, and $\mathbf{r}_c$ and $\mathbf{r}_g$ are the position vectors for the center of each computational cell and the center of gravity of the vehicle, respectively.

For modeling effects of a rotating fluid due to the axial spin of the lightcraft, a rotational boundary condition is employed. Fluid velocity in the normal direction is set to 0 on the wall,
and tangential velocity on the vehicle surface $u_t$ is determined by an arm’s length from the vehicle axis to the body surface $R_w$ and the velocity of the gyro spin $P$ [25]:

$$u_t = R_w P.$$  

(9)

The pressure gradient for the normal direction on the wall boundary is estimated by

$$\frac{\partial p}{\partial n} = \rho \frac{u_t^2}{R_w}.$$  

(10)

When the rotating fluid settles to a steady state, the laser beam is irradiated to the vehicle.

For comparison with the fluid-orbit coupling calculation, aerodynamic coefficients of a non-spinning lightcraft for steady flow are employed by the following forms [11]:

$$C_D = 0.3928\zeta^3 - 0.8463\zeta^2 + 0.0398\zeta + 0.731,$$  

(11)

$$C_L = 0.1993\zeta^5 - 0.3317\zeta^4 - 0.5531\zeta^2 - 0.0316\zeta,$$  

(12)

$$C_M = 0.1598\zeta^6 - 0.6619\zeta^5 + 0.8794\zeta^4 - 0.3585\zeta^3 - 0.0583\zeta^2 + 0.080\zeta,$$  

(13)

where $C_D$, $C_L$, and $C_M$ are the aerodynamic coefficients of drag, lift, and pitching moment, respectively. These coefficients are the functions of the angle of attack $\zeta$.

3. Simulation Conditions

A type 200-5/6 lightcraft [3] is assessed in the present study. The vehicle diameter is 122 mm, and the vehicle mass is 32.5 g. Initial spin rate is set to 10,000 rpm based on past study [11]. The laser beam energy is deposited into the steady-state solution given by the rotational boundary using a ray-tracing method [26]. A 420-J laser beam is numerically divided into $\sim$3,000 rays for the ray-tracing, and the laser rays reflected by a parabolic mirror equipped on the lightcraft are focused inside the shroud. The laser intensity is set to be spatially uniform within a cross-section of 7.2-cm radius [11]. The efficiency of laser energy absorption by plasma is assumed to be 60% so as to adjust the generated impulse to the experimental data [11].

4. Results and Discussions

4.1. Coupling effects for angular and translational velocities

When the laser beam is irradiated to the vehicle with lateral y-offset of $-50$ mm and no angular offset, an asymmetric blast wave is generated from the focal point (ring) in the negative side of the y-axis (figure 2(a)). This strong blast wave rotates the vehicle in a clockwise direction. The counter-clockwise flow is consequently induced by the feedback of the angular velocity because the flowfield computation is conducted in the body-fixed coordinate system, and this counter-clockwise flow provides the restoring moment against the vehicle rotation (figure 2(b)).

Figure 3(a) shows that the angular velocity of the coupling calculation becomes about 0.4% smaller than the angular velocity in the case without the motion feedback. Non-coupling calculation is also conducted using the aerodynamic coefficients of steady flow (11)–(13). The angular velocity estimated by the coupling calculation becomes smaller in comparison with the case using the aerodynamic coefficients, that is, the restoring moments obtained by the aerodynamic coefficients are underestimated because the moment amplitude is not determined based on the rotational velocity of the vehicle. If the vehicle has no translational velocities, we can not obtain the restoring moments using the aerodynamic coefficients, and therefore, the coupling calculation is effective for predicting the vehicle rotation precisely.

The translational velocities in the body-fixed coordinate system are also fed back to the flowfield for modeling the pressure and viscous drags induced by the vehicle moving. The
resulting vehicle velocity becomes small as compared with the non-coupling cases with and without aerodynamic coefficients (figure 3(b)). In case the aerodynamic coefficients are employed, the drags caused by the vehicle motion are assessed as smaller size; thus, the fluid-orbit coupling calculation is needed for an accurate estimation of rapidly accelerated reaction.

![Figure 2](image2.png)

(a) Pressure distribution in a cross-section of $z = 0$ at $60 \, \mu s$

(b) Velocity vector of flowfield at $1000 \, \mu s$

Figure 2. Pressure distribution and velocity vector for y-offset of $-50$ mm and no angular offset.

![Figure 3](image3.png)

(a) Time evolutions of angular velocity $\sqrt{Q^2 + R^2}$

(b) Time evolutions of translational velocity $U$

Figure 3. Time evolutions of angular and translational velocities in the coupling case and non-coupling cases with and without aerodynamic coefficients.

4.2. Comparison between impulse data model and coupling calculation

In conventional schemes for modeling the impulsive vehicle motion, the impulse data examined by the experiments is simply added to the velocity at each time step to avoid the temporal integration of time-dependent thrust based on an assumption that the blast wave interaction finishes promptly. At the laser incident timing, the vehicle velocity is updated by the linear equations of motion as follows [11, 14]:

$$m U_1 = m U_0 + I,$$

(14)
where $\mathbf{U}_1$ is the updated velocity vector, $\mathbf{U}_0$ is the present velocity vector, $\mathbf{I}$ is the impulse vector examined by experiments, and $m$ is the vehicle mass. By the simple approach using the impulse data, sharp thrust during the blast wave interaction is ignored. However, because the vehicle is rapidly accelerated during the interaction with the shock wave, it is necessary to integrate the unsteady force for an accurate prediction of the impulsive reaction. We compare the simple model shown by (14) with the motion prediction based on the fluid-orbit coupling approach.

A single pulse is irradiated with no lateral and angular offsets. Using our hydrodynamic calculation code, impulse data is estimated by the integration until the blast wave interaction vanishes (1000 $\mu$s), and this impulse is added to initial condition in solving the equations of motion using the aerodynamic coefficients. On the other hand, the fluid-orbit coupling calculation is conducted until 1000 $\mu$s by evaluating the instantaneous force of the shock wave to compare with the simple model.

A positive thrust is obtained when the shock wave touches the rear surface of the vehicle at 10 $\mu$s, and a positive force is continuously generated for a longer time (figure 4(a)). As a result, the vehicle is instantaneously accelerated, and the velocity overshoot occurs as compared with the simple model using the impulse data (figure 4(b)). After 800 $\mu$s, the vehicle velocity has an almost constant speed due to the vanishing of the blast wave interaction, while the velocity amplitude decreases gradually because of the gravity and aerodynamic drag. The flight height of the simple model is underestimated in comparison with the direct integration using the coupling simulator because the rapid acceleration is not reproduced in the simple case. At 1000 $\mu$s, the height of the coupling calculation becomes 6% larger than the simple model, and this prediction error can be serious if multiple pulses are irradiated into the vehicle to fly into 10–100 km-order altitude. It is better that the time-dependent force is directly integrated during the shock interaction regime by the coupling scheme for the accurate analysis of the vehicle motion.

![Figure 4](image_url)

(a) Time evolution of thrust in coupling case  
(b) Time evolutions of velocity and height.

**Figure 4.** Time evolutions of vehicle thrust, velocity, and height with coupling calculation and simple model based on impulse data.

### 5. Conclusions

Using a three-dimensional hydrodynamic code coupled with 6-DOF equations of motion, the blast wave propagation and the flight motion of a laser-boosted vehicle were simulated by introducing the vehicle motion effect. By the motion feedback to the flowfield, the angular and translational velocities become lower than in the non-coupling case using the aerodynamic coefficients of steady flow. The restoring forces induced by the moving vehicle are underestimated if the force is estimated through the aerodynamic coefficients. Additionally, the simple model
using the impulse data was compared with the trajectory prediction by the coupling calculation. The coupling calculation yields rapid acceleration of the vehicle during the interaction with the blast wave, and the flight height becomes larger than the simply modeled case. It is essential to conduct the coupling calculation for the precise estimation of unsteady flying dynamics of the laser propulsion vehicle.

References
[1] Söderlund B 2006 Master’s Thesis, Luleå University of Technology
[2] Kantrowitz A 1972 Astronautics and Aeronautics 9 40–42
[3] Myrabo L N 2001 AIAA Paper 2001–3798
[4] Mead F B Jr, Messitt D G and Myrabo L N 1998 AIAA Paper 98–3735
[5] Scharring S, Eckel H A and Röser H P 2001 Beamed Energy Propulsion: Seventh International Symposium on Beamed Energy Propulsion, AIP Conference Proceedings 1402 115–131
[6] Sasoh A 2000 AIAA Paper 2000–2344
[7] Mori K, Komurasaki K and Arakawa Y 2004 Journal of Spacecraft and Rockets 41 887–889
[8] Katsurayama H, Komurasaki K and Arakawa Y 2002 AIAA Paper 2002–3778
[9] Katsurayama H, Komurasaki K and Arakawa Y 2009 Acta Astronautica 65 1032–2014
[10] Phipps C R, Reilly P R and Campbell J W 2000 Laser and Particle Beams 18 661–695
[11] Ballard C G, Anderson K S and Myrabo L N 2009 Journal of Computational and Nonlinear Dynamics 4 041005-1–041005-8
[12] Libeau M and Myrabo L N 2005 Beamed Energy Propulsion: Third International Symposium on Beamed Energy Propulsion, AIP Conference Proceedings 766 166–177
[13] Libeau M, Myrabo L N, Filippelli M and McHerney J 2002 AIAA Paper 2002–3781
[14] Kenoyer D A, Anderson K S and Myrabo L N 2008 Beamed Energy Propulsion: Fifth International Symposium on Beamed Energy Propulsion, AIP Conference Proceedings 997 325–337
[15] Takahashi M and Ohnishi N 2011 Beamed Energy Propulsion: Seventh International Symposium on Beamed Energy Propulsion, AIP Conference Proceedings 1402 132–141
[16] Takahashi M and Ohnishi N 2012 AIAA Journal 50 2600–2608
[17] Takahashi M and Ohnishi N 2012 AIAA Paper 2012–3302
[18] Wada Y and Liou M S 2006 AIAA Paper 2006–1358
[19] Van Leer B 1979 Journal of Computational Physics 32 101–136
[20] Toro E F 2010 Riemann Solvers and Numerical Methods for Fluid Dynamics, 3rd ed. (New York: Springer Press)
[21] Toro E F and Clarke J F 1998 Numerical Methods for Wave Propagation (London: Kluwer Academic Publishers)
[22] Hirsch C 1984 Numerical Computation of Internal and External Flows, Vol. 1 (New York: John Wiley and Sons)
[23] Spalart P R and Allmaras S R 1992 AIAA Paper 92–0439
[24] Skullestad A 1999 Modeling, Identification and Control 20 3–25
[25] Hirsch C 1984 Numerical Computation of Internal and External Flows, Vol. 2 (New York: John Wiley and Sons)
[26] Born M and Wolf E 1959 Principles of Optics, 1st ed. (New York: Pergamon Press)