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Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed six manuscript pages and three figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Propulsive Impulse Measurement of a Microwave-Boosted Vehicle in the Atmosphere

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Introduction

WE introduce the concept of a launcher boosted by electromagnetic waves: When electromagnetic waves are beamed from the ground intermittently and focused in the atmosphere, breakdown occurs near the focus, and plasma is formed. The plasma absorbs the following part of beamed energy and expands outward generating shock waves. The shock waves reflect on a nozzle surface of a vehicle, generating impulsive thrust. Because the energy is provided from the ground and the atmospheric air is utilized as a propellant, neither energy source nor propellant need to be loaded onto the vehicle. Consequently, this type of launcher can achieve a high payload ratio at a remarkably low launch cost.

Generally speaking, both lasers and microwaves can be used for energy beaming from the ground to vehicles; many experimental and analytical studies have been carried out on laser-boosted launchers.[1−3] On the other hand, very few studies have been conducted regarding microwave-boosted launchers, mainly because of poor directionality of the microwave beam. However, this is not necessarily true when the transmission distance is in the range of 100 km.

Use of microwaves offers several advantages. Energy conversion efficiency from electricity to microwaves can exceed 90%. Also, development costs for high-power microwave generators would be much lower than those for high-power laser oscillators. Especially, phased-array technology enables us to realize a single large-diameter coherent beam.[4]

This study is intended to evaluate performance of a microwave-boosted vehicle through launch tests on the ground.

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Experimental Equipments and Methods

Vehicle Models

We fabricated and tested three models of microwave-boosted vehicles. A parabola-shaped model made of duralumin was fabricated to ensure precise beam focus. Nozzle-exit diameter and parabola focal lengths were 90 and 15 mm, respectively, as shown in Fig. 1a. The vehicle weighed 95 g.

A polymer membrane was used to configure the parabola nozzle, as shown in Fig. 1b, because the duralumin model was too heavy to lift high with the microwave power available in this experiment. Although the polymer model size and shape were identical to the duralumin one, it weighed only 3 g. Membrane-parabola fabrication technology was originally developed at the National Aerospace Laboratory of Japan for a sunlight concentrator for solar thermal propulsion.[5]

We also addressed the relationship between vehicle length and thrust performance. A conical nozzle with a cylinder body of variable length was made as shown in Fig. 1c. Its structural material was a thin plastic sheet. Body length was varied from 60 to 120 mm and corresponding model weight was varied from 9.5 to 19.5 g. The inner surface of the cone was covered with aluminum foil. Although a cone does not focus a microwave beam tightly, we ignited plasma successfully with no misfiring.

Microwave Generator

A gyrotron microwave oscillator developed by the Japan Atomic Energy Research Institute was used in this study.[6] Table 1 lists its

Table 1 JAERI gyrotron specifications

Characteristic	Value
Frequency	110 GHz
Output power P	<1 MW
Pulse duration τ	0.175 ms–10 s
Output mode	Gaussian
Electrical efficiency	50%

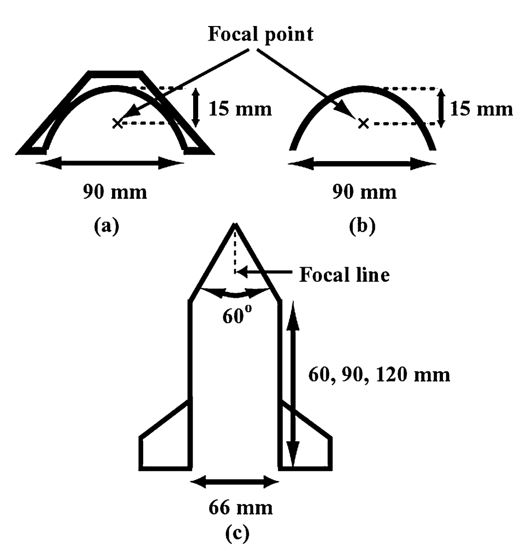

Fig. 1 Vehicle models: a) duralumin parabola model, b) polymer membrane parabola model, and c) plastic cone-cylinder model.

specifications. This high-power facility was originally constructed as a radio-frequency heating device for fusion reactor research. Pulse width τ is variable from 0.175 ms to 10 s. Output power P is almost constant during the pulse. The microwave beam was guided from the gyrotron to the launch site using a circular corrugated wave guide. Distance from the outlet window of the guide to the vehicle model was 30 cm; the beam waist was 20.4 mm.

Propulsive Impulse Measurement Methods

Propulsive impulse was measured by three methods using horizontal and vertical beaming apparatus. The horizontal beaming setup is shown in Fig. 2. The duralumin parabola model was mounted on a linear-motion-guide rail, which restrained its movement only in the thrust direction. Propulsive impulse was deduced from the maximum output signal of the force transducer because the characteristic response time of this measurement system (typically 15 ms) is one order of magnitude longer than the time in which thrust is imparted: Shock reflection is completed in about 0.1 ms from the ignition, and then gauge pressure on the parabola surface would be kept positive for the microwave pulse width of 0.175–1.0 ms. Even if the air refilling process is taken into account, total duration is estimated at several ms. Calibration of force transducer signal was conducted using an impulse hummer.[7] The result is shown in Fig. 3.

Figure 4 shows the vertical beaming setup. Altitude h was measured with a laser displacement sensor; its ejection velocity v_0 was estimated by analyzing images of vehicle motion taken at $t = 2 - 10$ ms by a high-speed video camera (1000 fps).

Propulsive impulse I is a function of h or v_0, as

$$I = M\sqrt{2gh} = Mv_0 \tag{1}$$

where M and g represent vehicle mass and gravitational acceleration, respectively. The aerodynamic drag was negligibly small because h and v_0 were kept less than 0.5 m and 3 m/s, respectively, by adding weights to the models.

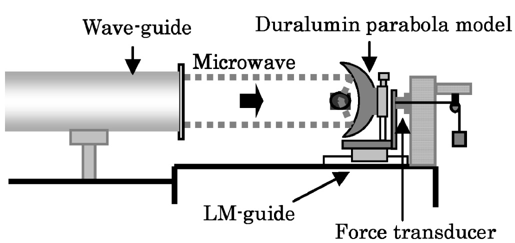

Fig. 2 Horizontal beaming setup.

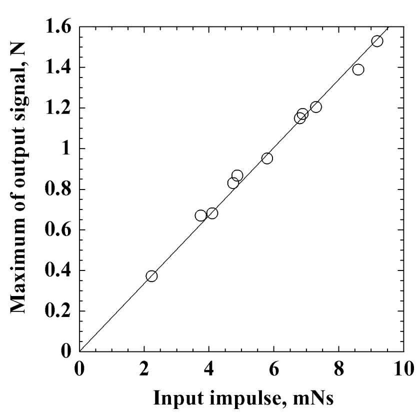

Fig. 3 Calibration result of the force transducer signal using an impulse hummer.

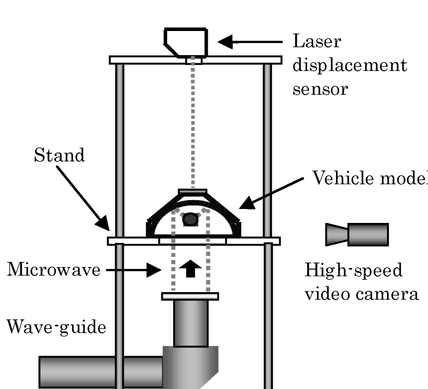

Fig. 4 Vertical beaming setup.

Results and Discussion

Validation of Thrust Measurement Methods

Figure 5 shows the propulsive impulse obtained with the duralumin model. Both vertical and horizontal beaming were tested. A coincidence in measured propulsive impulse was obtained by these methods. The propulsive impulse could not be deduced from v_0 because v_0 was very small, and the camera had insufficient spatial resolution to estimate it.

Figure 6 shows the propulsive impulse obtained with the polymer membrane model. Vertical beaming was conducted. Equivalent impulses were obtained from h and v_0. Impulse measurement with a force transducer was impossible because of its poor rigidity.

Consequently, it was found that these three methods yield equal propulsive impulses.

Performance Characteristics

Figure 7 shows the momentum-coupling coefficient C_m, defined as

$$C_m = I/P\tau \tag{2}$$

We compared duralumin and polymer membrane parabola models. The polymer membrane modelC_m was about half that of the

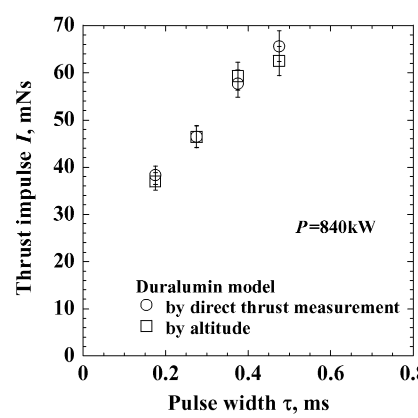

Fig. 5 Correlation between direct thrust measurement and thrust estimation from the altitude.

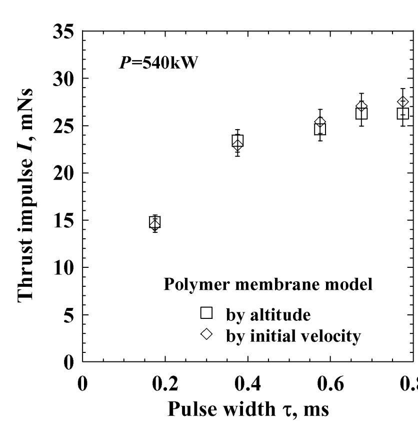

Fig. 6 Correlation of estimated propulsive impulses from altitude and ejection velocity.

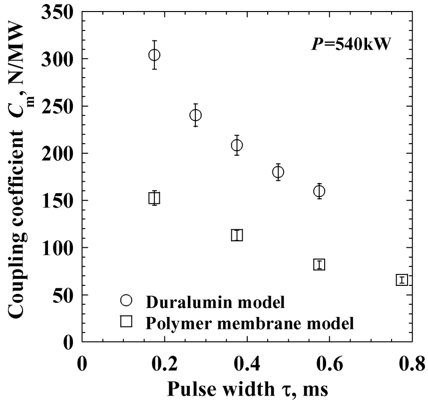

Fig. 7 Momentum-coupling coefficient.

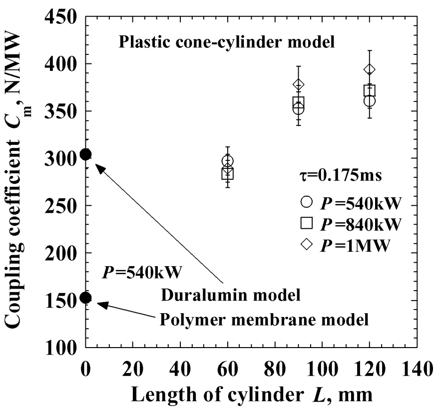

Fig. 8 Momentum-coupling coefficient and vehicle length.

duralumin model. This would be because the polymer membrane parabola was less rigid than the duralumin one, and shock reflection on the membrane became inelastic.

For both models C_m decreased with τ. This would be because, in the long pulse case, most of the energy was provided to the plasma developed outside of the parabola, and the pressure of the plasma was not converted to the thrust. Optimum pulse width for this scale of parabola would be shorter than 0.175 ms.

Figure 8 shows measured C_m for the cone–cylinder model along with those for the parabola models. It was deduced from v_0. C_m increased monotonically with the length of cylinder L. This indicates that the pressure of plasma was effectively converted to thrust by the cylinder portion of the model. The effect of rigidity of the cone–cylinder model would be similar to that of the membrane model.

Maximum C_m of 395 N/MW was recorded at $\tau = 0.175$ ms, $P = 1$ MW, and $L = 120$ mm. This value was comparable to those of laser-boosted vehicles.[7–9]

Conclusions

Using a 1-MW gyrotron, microwave-boosted vehicle models were launched, and propulsive impulse was measured by three methods. Results showed good agreement among measurement methods.

We estimated the momentum-coupling coefficient from the measured propulsive impulse. As a result, the maximum coupling coefficient of 395 N/MW was obtained with the cone–cylinder model. This value was comparable to those of laser-boosted vehicles.

The coupling coefficient will be increased further by optimizing pulse width and vehicle length as well as by increasing rigidity of the vehicle structure.

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Optimal Ascent Trajectory for Efficient Air Launch into Orbit

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Introduction

SINCE early in 2001, various teams of contractors have been funded for the Responsive Small Cargo Affordable Launch (RASCAL) project.[1] The stated goal of the RASCAL project is development of a low-cost, small-satellite launcher with the capability of delivering a 50–75-kg payload to low Earth orbit (LEO). The initial concept being pursued is that of miniature rocket launch from an airbreathing carrier aircraft at high altitude to provide independence from use of a dedicated launch facility (with a significant saving in ground-support costs). The critical part of the concept is the feasibility of developing a new type of carrier aircraft with a "souped-up" turbojet engine as a reusable booster stage. Air launch of the rocket would occur at about 130,000 ft (39.6 km) with the rocket continuing its ascent to orbit and the carrier aircraft descending for a runway landing. It is anticipated that the gross takeoff weight of an aircraft and a 6000-lb rocket would be about 22,000 lb.

There has been only one air-launch system developed among all the U.S. space launch vehicles. The Pegasus XL[2] is a three-stage, solid-propellant rocket that is air launched horizontally from an L-1011 TriStar aircraft for LEO. The rocket has a delta wing attached

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