A Plasma and Shockwave Observation with Pulse Repetition in a Microwave Boosted Thruster

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An experiment on repetitively pulsed microwave beaming propulsion was conducted. A 170GHz high power gyrotron was used for a repetitive-pulse microwave source. The propagation velocity of an ionization front and a shock wave in a cylindrical thruster model was. Pressure histories under multi pulse operationwith various repetition frequency from 15 Hz to 60 Hz. These propagation velocities were identical in any cases, and found decreased with the interval time. The velocity of shock wave and pressure in the thruster changed with the repetition frequency. Although impulsive thrust deduced from the pressure history was increased with the interval time, it was saturated at the repetition frequency about 20 Hz.

Nomenclature

A = area of thrust wall of the thruster
$C\mathrm{m}$ = momentum coupling coefficient
I = thrust impulse
L_{thruster} = length of the thruster
p_1 = pressure of atmosphere
p_2 = pressure behind of shock wave
p_3 = pressure behind of rarefaction wave
U = propagation velocity of shock wave
$U_{\mathrm{expansion}}$ = propagation velocity of expansion wave

I. Introduction

RECENTLY, researches on beamed energy propulsion (BEP) are held in many groups using a laser beam. Because propulsive energy is provided by beamed energy transmitted from outside, the vehicle is not necessary to load an energy source by itself and achieves the high-payload ratio.[1]

In BEP, once the energy beam station is built, it can be used during many launch counts. The development cost for a beam oscillator is predominant when the launch count is few. The development cost for microwave oscillators is expected two orders of magnitude lower than that of laser oscillators, because a GW-class oscillator would be achievable by clustering existing high-power oscillators using the phased array technology. Then, microwave beaming propulsion is expected to achieve lower launch cost with fewer launch counts than laser beaming propulsion.[2]

We had conducted a single pulse experiment using a conceptual thruster with a 1MW microwave beam. The measured momentum coupling coefficient C_{m}, defined as the ratio of propulsive impulse to input power, was over 400N/MW.[3][4] In 2004, C_{m} at multi pulse operation was measured. In the experiment, two pulses were inputted and the impulse imparted by the second pulse was deduced for the interval time duration 10ms and 15ms conditions. C_{m} decreased in both conditions, but it decreased much at the 10ms interval condition. The reference concluded that the decrease in C_{m} was due to the scavenging rate.[5]

Both plasma and a shock wave play the important role in the energy conversion process of the microwave beaming propulsion. In 2005, an observation on plasma and the shock wave in the thruster model with a cylindrical tube at single pulse operation was conducted. The plasma observation using a high speed framing camera shown that the ionization front of plasma propagated towards the microwave radiation source at super sonic velocity in the tube.

At the same time, the measurement result of the shock wave velocity in the tube shown that the shock wave also propagated in the same velocity of the ionization front when its velocity was supersonic. This result indicated that the atmospheric millimeter-wave plasma caused isometric heating and formed a shock wave in its supersonic propagation. With the result, the thrust producing model based on shock wave propagation was proposed and thrust was estimated.[6][7]

In this study, to investigate the effect of the pulse repetition to the propagation process of an ionization front of plasma and a shock wave, an observation of plasma and a shock wave was conducted.

II. Thrust Generation Model

We have studied a repetitively-pulsed microwave beaming thruster. Our concept is explained as follows: When a high power pulsed microwave beam is provided into a focusing reflector, an atmospheric discharge arises. The induced plasma absorbs the microwave and its ionization front propagates at the supersonic velocity on the microwave beam while generating a shock wave. The plasma behind the shock wave is heated isometrically and drives the shock wave further. The pressurized air imparts impulsive force on a thrust wall. The exhaust and air-refill process follows it, and then a microwave pulse is inputted again. At the point of cycle, it is resemble to the repetitivly-pulsed laser thruster. However, as the pulse duration provided by conventional high power microwave oscillator is far longer than that of laser, the thrust generation model of a microwave beaming thruster is explained in the analogy of a pulse detonation engine (PDE). In a PDE, a detonation wave starts from a thrust wall and propagates towards the exit.[8][9] In a microwave beaming thruster, a shock wave supported by microwave plasma propagates in the tube instead of a detonation wave. The shock wave supported by microwave plasma propagates in supersonic velocity U. The shock wave makes a sharp pressure increment from p_1 to p_2 as shown in Fig. 1. Then, a rarefaction wave follows the shock wave and pressure in the tube decreases to p_3. The pressure behind the rarefaction wave p_3 is steady until the shock wave arrives at the tube exit.

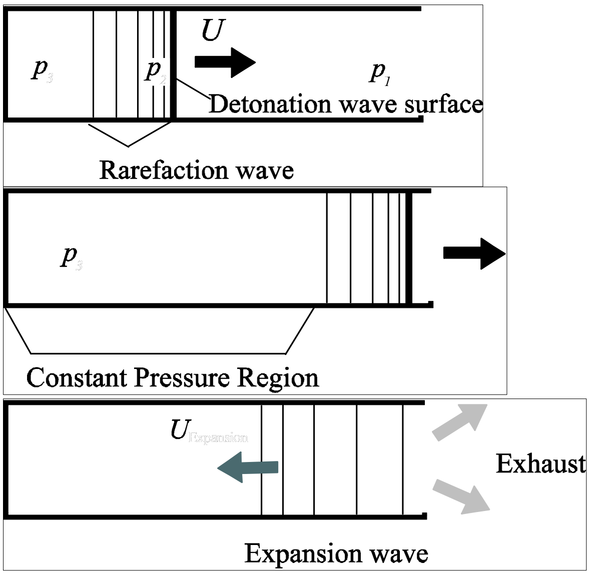

Figure 1. Schematic figures of thrust producing model.

After the termination of shock wave propagation, an expansion wave goes upstream from the tube exit towards the thrust wall at velocity $U_{\text{expansion}}$, which is same to the sonic velocity of the constant pressure region. The pressurized air in the thruster is exhausted and pressure at the thrust wall decreases to the atmospheric pressure.

Total impulsive thrust I in one-cycle operation is calculated as Eq.(1).

$$I = \int (p - p_1) A dt = (p_3 - p_1) A T_{\text{plateau}} \tag{1}$$

Here, A is the area of thrust wall, and T_{plateau} is the duration time of constant pressure defined as

$$T_{\text{plateau}} = \frac{L_{\text{thruster}}}{U} + \frac{L_{\text{thruster}}}{U_{\text{expansion}}} \tag{2}$$

III. EXPERIMENTAL APPARATUS

A. Microwave Generator

As a microwave beam generator, a high power gyrotron was used. It was developed by Japan Atomic Energy Agency (JAEA) as a microwave power source for the electron cyclotron heating and electron cyclotron current drive (ECH/ECCD) system of International Thermonuclear Experimental Reactor (ITER). Its frequency is 170GHz, and its nominal output power is up to 1MW. At the single pulse operation, the microwave pulse duration is variable from 0.1msect to 10sec and its power is almost constant during the pulse duration.[10][11]

In the gyrotron, microwave is oscillated through the interaction between accelerated electron beams and electromagnetic waves by a cyclotron resonance maser in a cavity with magnetic fields. In this study, to provide microwave pulses repetitively, the acceleration voltage of an electron beam was modulated and the oscillation mode in the cavity was controlled. The repetition frequency was settled 15 Hz to 60 Hz. A typical power history is shown in Fig.2. The pulse duration τ and peak power P of each pulse were about 2 ms and 200 kW, respectively.

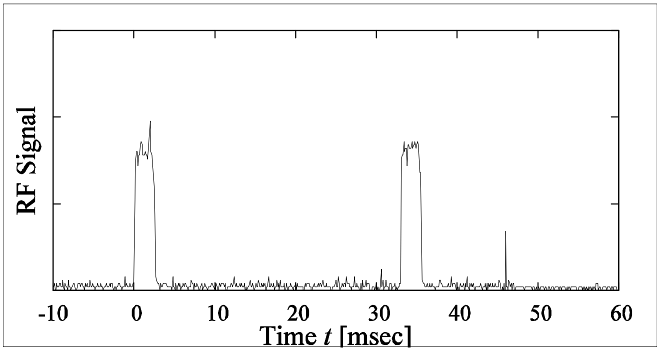

Figure 2. Typical record of microwave pulses. P=200kW, Repetition rate 15Hz

A microwave beam is transmitted through a corrugated waveguide to the experiment site. The output microwave beam was a fundamental Gaussian beam with a 20 mm waist.

B. Measurement Apparatus for thrust measurement

For thrust measurement, conical thruster models and a cone-tube thruster model were used. The conical thruster models' generating line length were 40 mm and 90 mm, and both apex angle were 60 degrees. The microwave beam was inputted from the base and focused on the centerline. A cone-tube thruster model had a conical nose with 60 mm generating line length and 60 degrees apex angle and cylindrical tube body with 90 mm length and 60 mm diameter. The microwave beam was inputted from the tube exit and focused on the centerline by the conical nose reflector, initiating plasma. The length from the top of the nose to the tube exit L_{thruster} was 111 mm.

Thruster models were launched vertically and their flight trajectories were recorded using a laser displacement gauge. The experimental setup is shown in Fig.3. Typical flight trajectories at both single and multi pulse operation are plotted in Fig.4. The initial velocity was calculated from the trajectory and the impulsive thrust was deduced for pulse by pulse.

C. Measurement Apparatus for Pressure History

A thruster model composed of a cylindrical tube with a conical nose was used. The microwave beam was inputted from the tube exit and focused on the centerline by the conical nose reflector, initiating plasma. A shock wave and ionization front of plasma propagates through the cylindrical tube absorbing the microwave beam during

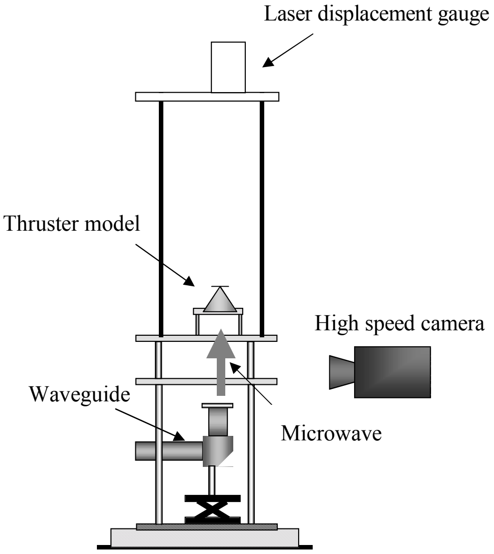

Figure 3. Schematic of the setup for vertical flight experiment.

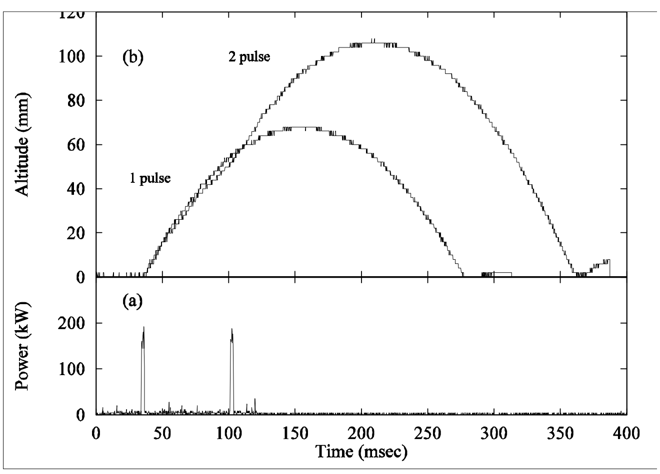

Figure 4. Typical flight trajectory and microwave pulse history. P = 200 kW, repetition rate 15 Hz,

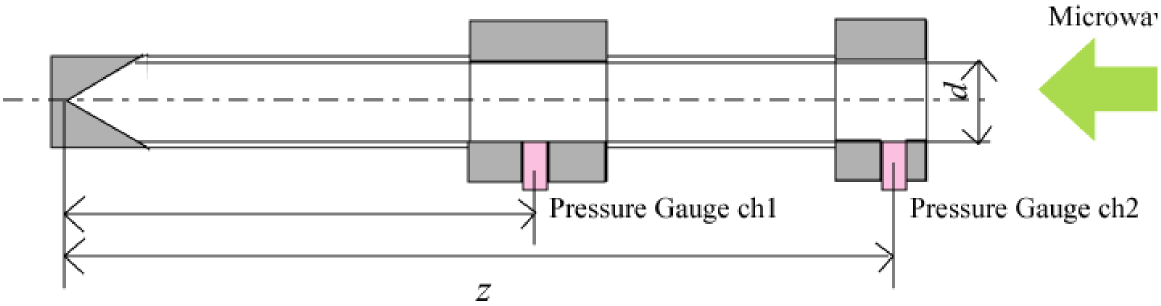

Figure 5. Schematics of pressure history measurement setup.

the pulse. This thruster model has the same thruster shape as that used in the flight experiment.

To deduce the velocity of a shock wave, Two flush-mount pressure gauges were settled at the cylindrical tube as shown in Fig.5 The measurement was conducted at z = 320, 370, 420, and 480 mm, here z was the position from the top of the nose. The total length of the thruster L_{thruster} was 500mm. The tube diameter d was 60 mm.

The pressure histories in the thruster were measured using a high-speed pressure gauge (Kistler's 603B). The signal of the pressure gauge was processed using a charge amplifier (Kistler's 5011B).

IV. EXPERIMENTAL RESULT AND DISCUSSION

D. Thrust Measurement Result by the Vertical Flight Experiment

Thrust measurement under the multi pulse operation was conducted. Two pulses with various interval durations were inputted into the thrusters at each operation.

Figure 6 shows the dependence of the thrust impulse imparted by the second pulse on the repetition frequency. When the repetition frequency is smaller than the critical frequency, the impulse saturates. Their critical frequency depends on with the thruster scale. For the 40 mm conical thruster, its critical frequency was 50 Hz. However, for the 90 mm conical thruster and the cone-tube thruster, their critical duration was larger than 30 Hz.

E. Result of Pressure Measurement

For the pressure history measurement at the multi pulse operation, two pulses were inputted into the thruster model. U and p_3 at the second pulse were deduced for various repetition frequency conditions.

Figure 7 shows the dependence of U on the repetition frequency. Here, the result of the single pulse operation was plotted at 0 Hz. As shown, U increased with the repetition frequency. This would be because the air left in the thruster remained hot and its acoustic velocity was large, when the second pulse was inputted. Figure 8 shows the p_3

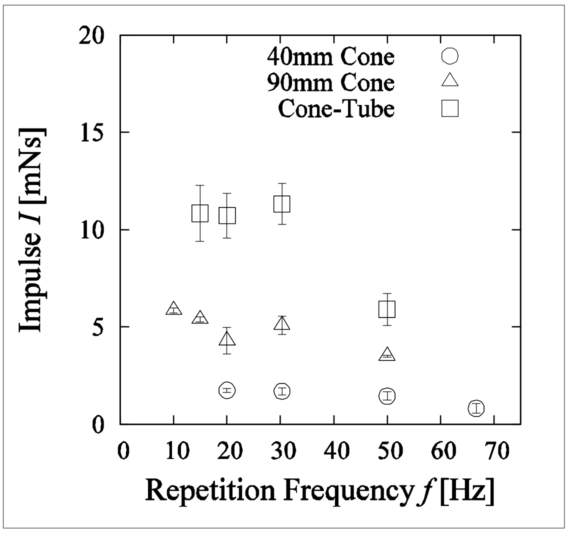

Figure 6. Result of thrust measurement on double pulsed vertical flight experiment. Dependence of impulse on repetition frequency.

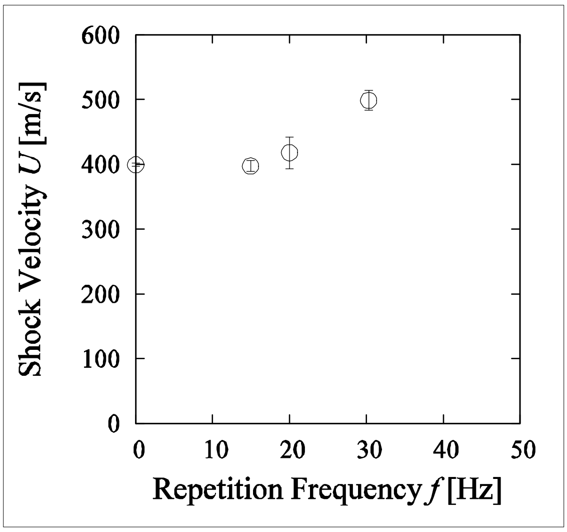

Figure 7. Dependence of shock wave velocity on repetition frequency.

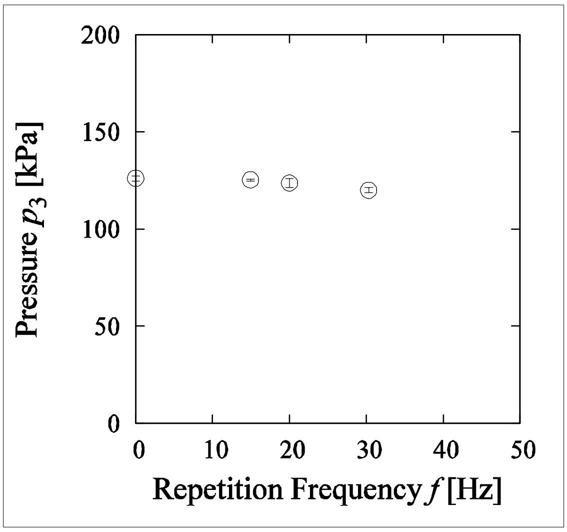

Figure 8. Dependence of pressure at constant epoch p_3 on repetition frequency.

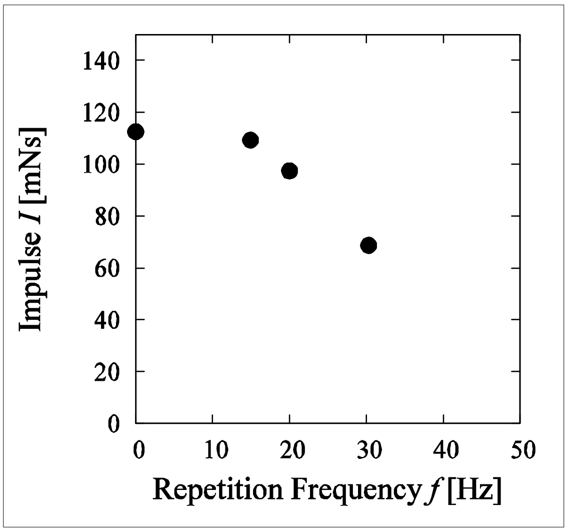

Figure 9. Dependence of estimated impulse I on repetition frequency.

dependence on the repetition frequency. p_3 slightly decreased with the repetition frequency.

I was estimated in a simplified way using Eqs. (1) and (2). Figure 9 shows the dependence of I on the repetition frequency. Although I increased with the repetition frequency, its decrease was allowably small at the frequency smaller than 20 Hz.

V. SUMMARY

Thrust measurement under the multi pulse operation was conducted. Measurement of the pressure history in the microwave beaming thruster with a cylindrical tube was also conducted.

As a result of thrust measurement by the vertical flight experiment, when the repetition frequency is higher than the critical frequency, the impulse decreases with frequency. Indeed, for low repetition rate dependence of impulse on the frequency was decreased. Their critical frequency depends on with thruster scale.

As a result of pressure histories measured under the multi pulse operation, the shock wave velocity was largely increased with the pulse repetition frequency, while and pressure variation in the thruster was very small. As a result, impulsive thrust was decreased with the pulse repetition frequency especially at the frequency higher than 20Hz.

Acknowledgments

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