Transportation of SPS using Microwave Rocket

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Introduction

The accessing cost to space remains one of the most important brakes against the development of human space activities. Many space projects remain at theoretical level because their realization costs are well far too important, mainly due to the launching part of the project. The current main technology to access orbit and space uses chemical rocket, but its cost and reliability put some important limitations on space projects. One famous example is the Space Power Satellite (SPS) which requires to send large and massive structures into space. Thus the transportation costs of the SPS are excessively high. For instance, in the case of a 4GW satellite, the total mass should be around 80 000t (solar panel: 20kg/kW), using a launcher like the Ariane V, the total transportation cost will be around 1 600 Billion $ (20 000$/kg). Therefore some new technologies are necessary to drastically decrease the cost of reaching space. The Microwave Rocket is one of the new technologies which are currently investigated. In such a rocket atmospheric air is used as propellant during part of the flight in dense atmosphere. Thrust is obtained by exhaust of compressed air through microwave detonation. Such technique owns some obvious advantages. It is an Air-Breathing system, less propellant is needed which results in a higher payload ratio. It is a pulse detonation operative system, therefore the vehicle structure should be simpler (no turbo pump system is required like in chemical rocket). At last, the energy source remains on the ground (ground beam base), it is reusable and easy to maintain. In this paper, past research successes are briefly resumed. Then an analytical model of the thrust produced by a Microwave Rocket using reed-valve system is described and used to study some trajectories to GEO. At last some cost estimations are discussed.

Previous experimental successes

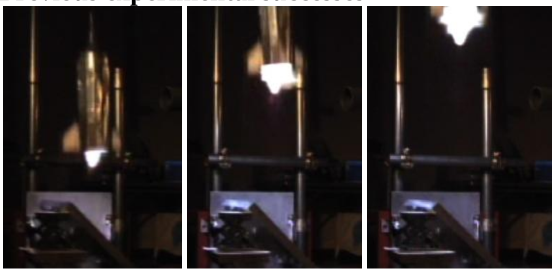

Fig. 1: 2009 demonstration photography

A first feasibility demonstration was made in 2003. During this early test, only a single pulse, of 0.4ms, launch was shown using a gyrotron which average output power was 930kW, and average power density $100 kW/cm^2$. In 2009, during a multi-pulse demonstration, a 2N thrust was achieved and a 129g rocket model (without air-breathing system) was launched up to 5m. Recently (2011), during a new multi-pulse experiment using a rocket model with reed-valves as air-breathing system, 30N thrust was achieved during 25ms.

Analytical Thrust Model of Microwave Rocket in Air-Breathing mode

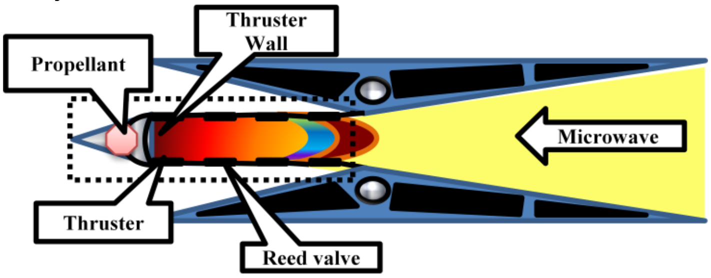

Fig. 2: Concept of Microwave Rocket using reed-valves

One system of Microwave Rocket proposed at the University of Tokyo is a rocket based on the Pulsed Detonation Engine (PDE), in which the refilling is ensured by reed valves during air-breathing mode. A simple scheme of this rocket is shown on figure 2. In this PDE cycle a microwave beam enlightens the gas in the thruster chamber, plasma is created and a first wave is generated which propagates toward the thruster exit. Then different waves followed the first one. The model is divided into three successive steps of calculation. In the first step, a first wave, detonation one or normal shock one depending on the power density, is propagating toward the thruster exit followed by an expansion wave. In the model, only the case where a detonation wave is produced is considered. The detonation wave velocity (U_D) is determined using the equation proposed by Shimaga Y.[1)] which is solved numerically through Newton-Raphson's method:

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$$U_\mathrm{D} = \sqrt{\frac{(\gamma^2-1)\eta S_\mathrm{av}}{2\rho_1 U_\mathrm{D}} + a_1^2} + \sqrt{\frac{(\gamma^2-1)\eta S_\mathrm{av}}{2\rho_1 U_\mathrm{D}}} \tag{1}$$

(a_1: sound velocity before the detonation wave, ρ_1: air density before the detonation wave, η: attenuation coefficient, S_av : average beam power density).

The Chapman-Jouguet theory and rarefaction wave theory[2-3] are used to model the wave and determine the overpressure after the expansion wave. The impulse generated (I_1) is calculated using the overpressure at the thruster wall (P_w1):

$$I_1 = A(P_\mathrm{w1} - P_\mathrm{f})\tau_1 \tag{2}$$

(A: thruster transversal area, τ_1: first step duration, P_f: atmospheric pressure in front of the rocket)

The second step starts when the detonation wave reaches the thruster exit. Another expansion wave is then generated and propagates toward the thruster wall. Through this second expansion wave, the pressure inside the thruster decreases. After that the second expansion wave has reflected on the thruster wall, pressure oscillations occur in the thruster. Using some simplified assumptions, the pressure evolution at the thruster wall is established and the impulse generated during this step (I_2) is deduced from it with the following formula:

$$I_2 = A(P_\mathrm{w1} - P_\mathrm{f})(t_\mathrm{b} - \tau_1) + A\int_{t_\mathrm{b}}^{t_2} (P_\mathrm{w}(t) - P_\mathrm{f})\,\mathrm{d}t \tag{3}$$

where t_b is the beginning time of decrease pressure at the thruster wall (the second expansion wave reaches the thruster wall) and t_2 is such that $P_\mathrm{w}(t_2) = P_\mathrm{f}$. At last, the third and last steps begin during the first pressure oscillations once the pressure in the thruster goes under the pressure near the reed valves. At this moment, the reed valves open and the refilling begins. The mass flow through the reed valves system is modeled as the mass flow through a solenoid reed valve where characteristics parameters where determined through experimentation.

$$\dot{m} = \beta_\mathrm{reed}.P_\mathrm{f}\rho_\mathrm{f}\sqrt{\frac{T_\mathrm{f}}{T_\mathrm{in}}}\sqrt{1-\left(\frac{P_\mathrm{in}/P_\mathrm{f} - \mathrm{b}_\mathrm{reed}}{1-\mathrm{b}_\mathrm{reed}}\right)^2} \tag{4}$$

$\beta_\mathrm{reed} \approx 0.0027\ \mathrm{Pa^{-1}.m.s^{-1}}$ and $\mathrm{b}_\mathrm{reed} \approx 0.52$ (experimentally obtained)[4] ("in" index refers to the conditions inside the thruster, "f" index refers to the outside conditions near the air intake).

In the model, this step ends when the refilling is completed or when the second pressure oscillation should start (if the necessary time for a complete refilling is longer). Since pressure oscillations take place during this step, the impulse generated is supposed to be negligible. The Partial Filling Rate (PFR), ratio of fresh air volume to the total volume of the thruster chamber, is calculated:

$$PFR = \frac{Refreshed\ air\ volume}{Cylinder\ volume} = \frac{4\alpha_\mathrm{reed}\int_{t_2}^{t_3}\int_0^{L_\mathrm{th}} \dot{m}\mathrm{d}x\mathrm{d}t}{\rho_f D_\mathrm{th} L_\mathrm{th}} \tag{5}$$

(D_th, L_th refer to the diameter and length of the thruster, t_3: cycle duration, α_reed: ratio of opened reed valves area to thruster lateral area)

Finally the total impulse generated during one cycle is the sum of the two previous impulses. However the rocket works in multi-pulsed mode, and if the refilling is not entirely completed, the experimentation shows that the impulse after the first pulse decreases. In order to take care of this effect, a multiplication factor function of PFR (β) has been experimentally evaluated (if PFR < 1, β < 1; if not $\beta = 1$). Then the real impulse is: $I = \beta.(I_1 + I_2)$.

Thrust Power ratio (also called the momentum coupling coefficient) is calculated:

$$C_m = \frac{\int_0^{t_3} F.\mathrm{d}t}{E} = \beta\frac{I_1 + I_2}{P_\mathrm{em}.\tau_1} \tag{6}$$

One important thing to notice is that in the model, it is considered that, from Gaussian shape of the microwave beam, only 50% of the beam correctly reaches the thruster, therefore the total power emitted is $P_\mathrm{em} = 2S_\mathrm{av}A$. The duty cycle (microwave beam pulse duration on cycle time) is evaluated: $\Phi_\mathrm{duty} = \tau_1/\tau_\mathrm{cycle}$. At last the average thrust available is approached by: $F = C_\mathrm{m}.P_\mathrm{em}.\Phi_\mathrm{duty}$. Nevertheless the microwave rocket is expected to work in air-breathing up to an altitude of 100km, and so for different velocities of the rocket. Those conditions impact the refilling; therefore they have to be considered in the model and some assumptions are taken to do it. Mainly the microwave beam transmission from the ground to the rocket, but also ram-compressions effects at the front of the rocket impacting the air conditions at the entrance of the thruster have to be taken into account. To approximate these effects the standard atmosphere from the International Telecommunication Union Recommendations (ITU-R) is used[5]. The attenuation of the microwave beam by atmospheric absorption is estimated using the formulae of the ITU-R[6]. The results show that, in a vertical ascent case, with a launching base around 3km of altitude, attenuation under 10% should be possible. As for the ram-compressions effects, since the design of the vehicle is not yet determined, a very simple model is used. The air stagnates near the intake and when the flow is supersonic, the losses are equal to 30%.

Trajectory to GEO

The trajectory considered has been proposed by Katsurayama *et. al.*[7]. This trajectory rests on a Hohmann Transfer. The vehicle is launched from the equator (or the closest possible) on a vertical trajectory above the microwave beam base providing the microwave beam up to 100km altitude. Such a vertical acceleration greatly facilitates the use of BEP. Indeed, there is no need for complicate ways of tracking the vehicle. This idea is referred to as "beam riding through a light highway". The vehicle is accelerated via an air-breathing mode and rocket mode. The necessary cut-off velocity of the vertical acceleration V_0, about 10km/s, can be achieved with high acceleration. The vehicle is then left on a ballistic trajectory which apoapsis is beyond GEO radius and two boosts kicks (provided by electrical propulsion devices for instance) are used to complete the Hohmann transfer to the GEO. To study and model the trajectory, the rocket is treated as a punctual mass (m) and the general three-dimensional equations of motions for flight over a rotating spherical Earth[8] are used. Atmosphere is supposed to be at rest with respect to the Earth. Only a vertical ascent from the equator is considered, so several simplifications can be done. Thus, the following simplified equation system is obtained in the rotating Earth referential:

$$\frac{\mathrm{d}r}{\mathrm{d}t} = V \tag{7a}$$

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{F_\mathrm{T}}{m} - g + \omega^2 r \tag{7b}$$

$$2\omega V = \frac{F_\mathrm{N}}{m} \tag{7c}$$

With $F_\mathrm{T} = F.\cos(\alpha) - D$, $F_\mathrm{N} = F.\sin(\alpha)$ and $g = \mu/r^2$ (Earth's gravitational acceleration). In order to solve the system, a model of the drag is necessary. To approach and estimate the drag during the flight a simple model based on the equations of the USAF Stability and Control Handbook (DATCOM) is adopted. Equations of motion are solved while upward acceleration remains positive. The calculations are ended when it becomes negative. Therefore the potential of microwave rocket using reed-valves in air-breathing flight can be highlighted. The previously exposed thrust model is used to estimate different characteristics of the rocket during the flight, and particularly the average thrust. Calculations are lead using the 2 stages Runge-Kutta method for the time integration (with a step of 0.05s). Typical results are shown on the figures 3 to 5. All presented results are obtained assuming that the launching base is at 3km of altitude.

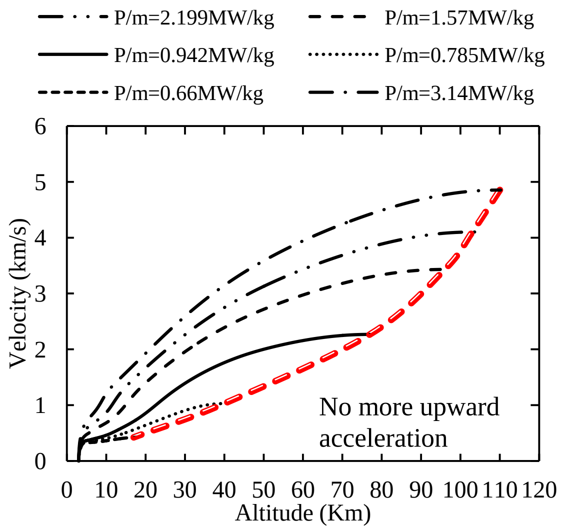

Fig. 3: Rocket velocity function of altitude. Results obtained for the following dimensions of the rocket: m = 500kg, L = 12m, D = 1.5m, L_{th} = 6.3m, D_{th} = 1m

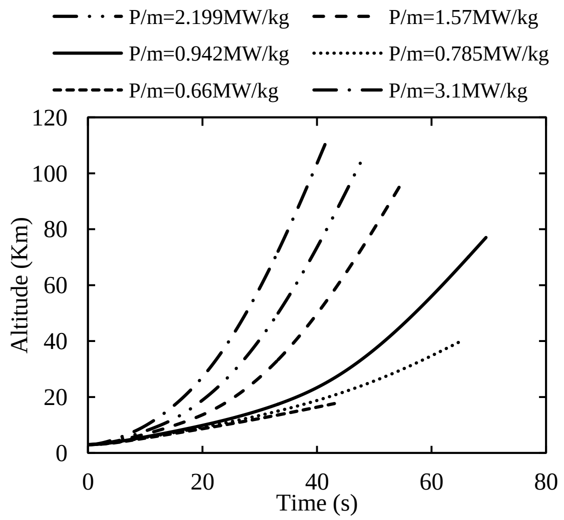

Fig. 4: Altitude as function of time. Results obtained for the following dimensions of the rocket: m = 500kg, L = 12m, D = 1.5m, L_{th} = 6.3m, D_{th} = 1m

The results show high capacities of the microwave rocket, which here seems to be able to accelerate, using only air-breathing mode, to an altitude up to 100km and a velocity around 4km/s (Mach number around 17). However in the presented results high stagnation temperature and dynamic pressure are also obtained during high powered trajectories. These induce that, from a material point of view, it is probably not possible to realize such trajectories. Constraints are necessary to limit the maximal acceleration and maximal dynamic pressure during the launch. Mainly the results show preliminary trajectories which highlight microwave rocket potential. These results also show that a rocket mode is inevitable to reach the cut-off velocity around 10km/s. Also in microwave propulsion case, with a limited size of the receptor (rocket) and emitter, the correct propagation is expected to be up to 100km. Therefore the rocket mode should probably start before the presented end of the air-breathing mode (red curve on the fig. 3). For instance a good moment to start the rocket mode could be the moment when the trajectory leaves the "optimal thrust road" (visible on the figure 5). Concerning the two necessary boost kicks the deltaV they have to provide is completely determined by the final conditions of the vertical ascent.

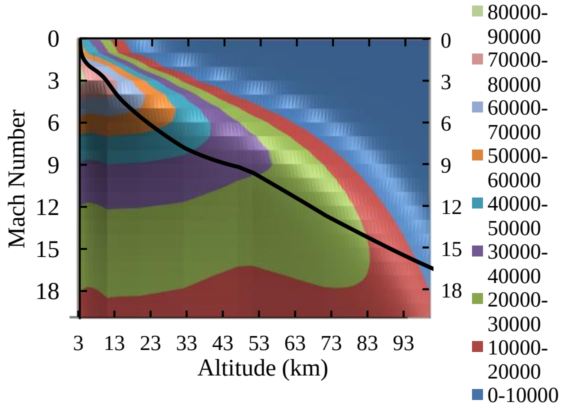

Fig. 5: Thrust (N) map and Mach number as function of altitude. Results for: m = 500kg, L = 12m, D = 1.5m, L_{th} = 6.3m, D_{th} = 1m; P/m = 2.199MW/kg

Cost estimations

In the case of Microwave Propulsion the costs can be separated in two main parts: the initial costs and the launching operations costs. The first part is constant and represents an initial investment which is amortized with the number of launches done using the same ground base. The second part represents the cost to spend necessarily at every launch.

The initial cost is the ground base cost which encompasses the microwave beam emitter cost and the antenna cost. The microwave beam is created using gyrotrons which current costs estimations is around 0.1M$ per megawatt emitted[)]. For the previously shown trajectories, the microwave power required is more than 1GW, therefore the cost of such emitter should be over 100M$. The cost of the antenna is estimated at 500M$.

The launching operations costs encompass the refurbishment costs of the ground base, the vehicle manufacturing costs, the propellant costs and the electrical costs. Some previous estimations, made for past model of microwave rocket which did not use reed-valves to unsure the air-breathing, are available. Vehicle manufacturing costs order of magnitude is around several millions $ and is expecting to decrease for each vehicle constructed. The cost of the n^{th} vehicle is supposed to follow the following formula[9)]: $C_{vehicle} = C_{initial} n^{\ln(0.85)/\ln(2)}$. Propellant costs are expected to be quite cheap (around 1$/kg) and the quantity of propellant small thanks to the availability of an air-breathing mode. At last, the current cost of electricity is about 0.1$/kWh. For the previous air-breathing trajectories shown, this represents a total electrical cost inferior to 1000$. The costs of one launch among n_L launches can be expressed with the following formula, which takes into account the amortization of the initial cost:

$$C_{launch} = (C_{gyrotron} + C_{antenna})/n_L + C_{refurbishment} + C_{vehicle} + C_{electrical} + C_{propellant} \quad (8)$$

In a previous paper, for a ground base of 5GW and a vehicle launching 301kg to GEO[9)], the costs estimations of reaching GEO using a microwave rocket were particularly low. For a base used for 200 000 launches the cost drops to 60$/kg, for 10000 launches the cost was around 600$/kg. All those estimations highlight the potential of the microwave rocket and its economical attractiveness. Even if no cost estimations are yet available for the new microwave rocket using reed-valves, recently proposed at the University of Tokyo, there are expected to be even more interesting than the previous one as the performances of the rocket are higher.

Conclusion

Past costs estimations for microwave rocket launch are very promising. Recently, with the new proposal of a microwave rocket using reed-valves system, the abilities of the microwave rocket seems even more appealing than in the past, as shown by the air-breathing trajectories presented. The analytical model used to plot these trajectories is particularly simple and has shown good agreement with some experiments. Now it is necessary to model a rocket mode for the new microwave rocket in order to achieve a complete trajectory calculation and then obtain new cost estimations. Even if a lot remains to be done, microwave rocket seems to be a very good candidate as a new mass driver which should be able to drastically decrease the costs of launching the SPS into space.

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