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# Engineering Notes

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## Evaluation of Effectiveness of Periodic Flight by a Hypersonic Vehicle

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### Introduction

PERIODIC flight has been proposed for long-range optimal hypersonic cruises, and its effectiveness has been examined [1–4]. Most studies have investigated optimal periodic flight trajectories in a cyclic flight. Rudd [4] and others adopted damped-periodic flight trajectories with the constraint that the ratio of kinetic to potential energy remained the same at the endpoints of a period. Large potential energy due to a high altitude can increase the speed and the range of the vehicle, even when the vehicle speed is low. In the present study, the total of the kinetic and the potential energies was specified at the endpoint of the flight. With this constraint, ranges of the damped-periodic and the steady-state flights were compared. This constraint will be practically effective as the standard for the periodic flight of hypersonic vehicles.

### Calculation Methods

In this study, the sounding rocket S-520 was presumed to be a booster rocket for launching a vehicle [5]. At an altitude of 35 km and a speed of Mach 7, a 200-kg vehicle was assumed to be released from the rocket. The wing area of the vehicle was 0.5 $m^2$ and its length was 2.5 m. Aerodynamic data for the vehicle were from [6]. The initial total energy of the vehicle was 583 MJ at the release from the booster rocket.

In the flight simulation, the earth was presumed to be a two-dimensional cylinder. The vehicle was a point mass and was controlled with the angle of attack. The equations applied to the vehicle were as follows [4]:

$$\frac{\mathrm{d}h}{\mathrm{d}r} = \tan\gamma\left(1 + \frac{h}{R_0}\right) \tag{1}$$

$$\frac{\mathrm{d}M}{\mathrm{d}r} = \frac{(T\cdot\cos\alpha - D - m\cdot g\cdot\sin\gamma)}{M\cdot a^2 m\cdot\cos\gamma}\left(1 + \frac{h}{R_0}\right) \tag{2}$$

$$\frac{\mathrm{d}\gamma}{\mathrm{d}r} = \left(\frac{L + T\cdot\sin\alpha - m\cdot g\cdot\cos\gamma}{M^2 a^2 m\cdot\cos\gamma} + \frac{1}{R_0 + h}\right)\left(1 + \frac{h}{R_0}\right) \tag{3}$$

$$\frac{\mathrm{d}m}{\mathrm{d}r} = -\frac{T}{g\cdot I_{sp}\cdot M\cdot a\cdot\cos\gamma}\left(1 + \frac{h}{R_0}\right) \tag{4}$$

where $h$, $r$, $\gamma$, $R_0$, $M$, $T$, $a$, $D$, $m$, $a$, and $I_{sp}$ are absolute altitude, range, flight-path angle, Earth radius, flight Mach number, thrust, angle of attack, drag, mass of the vehicle, speed of sound, and specific impulse, respectively. Acceleration due to gravity, $g$, and air temperature were presumed to be 9.8 $m\cdot s^{-1}$ and 260 K at all altitudes, for simplicity. Density was calculated as a function of altitude [7]. The maximum flight dynamic pressure was 100 kPa.

The vehicle was equipped with a dual-mode scramjet engine [8]. The width of the engine was 0.3 m, and its entrance area was 0.03 $m^2$. The engine operated either in the ramjet mode or the scramjet modes, with a variable contraction area ratio from 2 to 8 in its inlet. Figure 1 shows the profiles of the specific impulse and thrust coefficient $C_F$. Combustion efficiency was 0.8. The boundary layer, for which the thickness was one-tenth of the engine entrance height, flowed into the engine. The thrust was controlled by throttling, and the specific impulse was not affected by the throttling. The engine was assumed to be operable at a flight dynamic pressure larger than 50 kPa, because a sufficient pressure level in the combustor is required for combustion. Liquid hydrogen equivalent to 5% of the vehicle weight, 10 kg, was mounted on the vehicle.

In the damped-periodic trajectory, a flight with less decrease of total energy was calculated under the condition that the altitude did not exceed that of the initial condition. The longest range was calculated by iteration. In the steady-state flight, a slightly negative flight-path angle exhibiting minimum oscillations was calculated, with control by the angle of attack.

### Results and Discussion

The total energy of the vehicle was specified at the flight endpoint, and the flight ranges of the vehicle in the damped-periodic and in the steady-state flights were compared. Figure 2 shows the simulation results with the flight altitudes against the range. For comparison, the figure also shows the trajectory of a vehicle with the fixed angle of attack of 4 deg, with no thrust or control.

The vehicles descended to increase flight dynamic pressure after separation from the booster, and the engines started to operate around an altitude of 30 km under sufficient pressure conditions in both damped-periodic and steady-state flight conditions. Figure 3 shows profiles of the total energy and throttling in those two flight conditions. The engine produced larger thrust at lower altitude with denser air, whereas drag was smaller at higher altitude. In the damped-periodic flight, thrust was produced at lower altitude. The mean altitude of the damped-periodic flight increased after the powered flight, up to 1380 km.

All the stored fuel had been consumed by around 1300 km. The damped-periodic flight resulted in a range of 1380 km in 660 s, whereas with the steady-state flight, the range was 1280 km in 590 s at the endpoint of the powered flight, for which the total energy was

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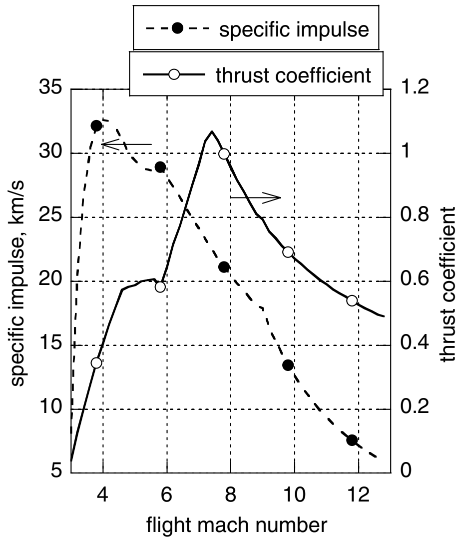


**Fig. 1 Specific impulse and thrust coefficient of the dual-mode scramjet engine.**

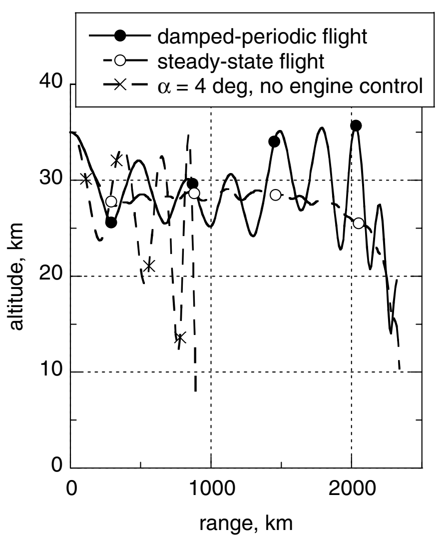


**Fig. 2 Trajectories of the damped-periodic and the steady-state flights. Trajectory of no thrust nor control is also plotted.**

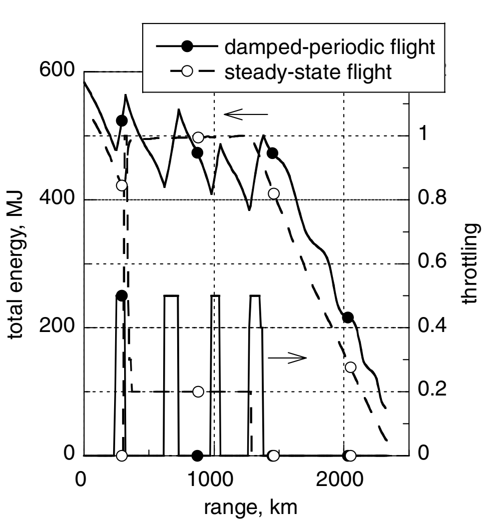


**Fig. 3 Total energy and throttling of the damped-periodic and the steady-state flights.**

500 MJ. The fuel consumption rates were 0.0072 $kg \cdot km^{-1}$ in the damped-periodic flight and 0.0078 $kg \cdot km^{-1}$ in the steady-state flight. An 8% range gain was attained with the damped-periodic flight, the value being similar to previous results [4].

In the postpowered flight condition, there was a 100- to 200-km difference in range between the damped-periodic and the steady-state flights. This was about a 10% range gain by the damped-periodic flight.

## Conclusions

Effectiveness of the damped-periodic flight was evaluated with the constraint that the total of the kinetic energy and the potential energy was specified at the endpoint of the flight. A hypersonic vehicle equipped with a dual-mode scramjet engine was assumed to be boosted by a solid rocket and flew with a specified amount of fuel, including its postpowered flight phase. The damped-periodic flight showed a range gain of about 10%, compared with the steady-state flight.

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