Proposal for Hybrid Kick Motor Experiment in Space Environment Using the S-520 Sounding Rocket

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観測ロケット S-520 を用いた宇宙環境下でのハイブリッドキックモータ実験の提案

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ABSTRACT

Small satellites are generally launched into space by rideshare, but due to the lack of a safe and fast propulsion system, they cannot move out of rideshare orbit, nor maneuver in a controlled manner. Nonetheless, it is expected that a space transportation network between major space transportation hubs (Earth, Moon, Mars, etc.) will be established in the near future. Hokkaido University is developing a safe and high-speed propulsion system (i.e. “kick motor”) that enable such small satellites to freely maneuver. This paper proposes an experiment to evaluate the thrust performance of the kick motor in a space environment (microgravity and near vacuum conditions) using the S-520 sounding rocket as a step towards achieving TRL-7.

Keywords: Hybrid rocket, kick motor, sounding rocket, deep space exploration, nitrous oxide

概要

小型衛星は一般的にライドシェアにより宇宙へ打ち上げられるが、安全で高速な推進系がないため、ライドシェア軌道から移動できず、軌道上を無秩序に周回する。これからの宇宙輸送では、主要な宇宙輸送ハブ（地球、月、火星等）間の宇宙輸送網の構築が予想される。北海道大学では、小型衛星に軌道変換の自由を与える安全で高速な推進系（キックモータ）を開発している。本論文では、TRL-7 達成へのステップとして、S-520 観測ロケットを用いた宇宙環境（微小重力・真空に近い状態）での北海道大学キックモータの推力性能を評価する実験を提案する。

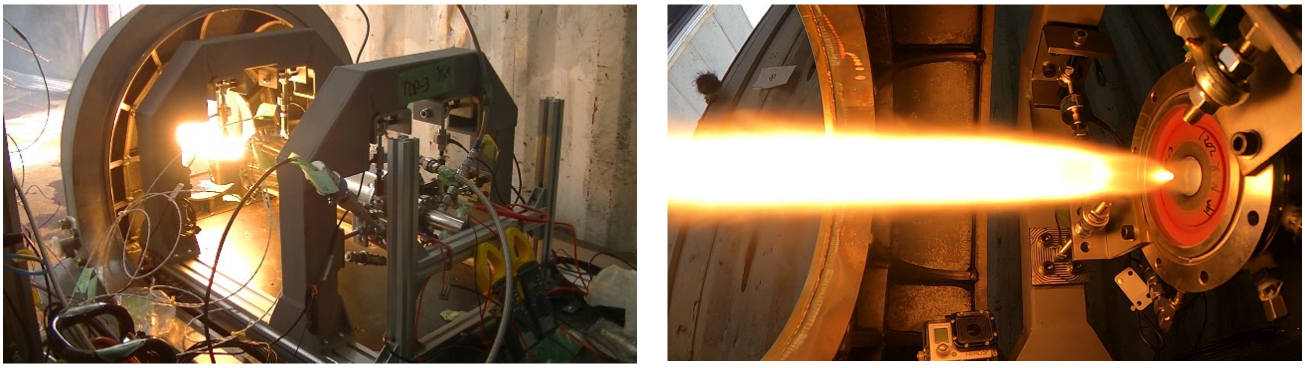
1. Kick Motor Development

Numerous small satellites are already being used or are in development as tools for reducing the cost of carrying out deep space exploration missions. For example, NASA is currently planning "Lunar Flashlight" to observe the South Pole of the Moon and "NEAScout" to observe asteroids near the Earth, both of which will employ CubeSats [1]. Meanwhile, JAXA developed the small satellite Procyon jointly with the University of

Tokyo in 2014 to demonstrate the performance of small satellites in deep space; Procyon is smaller than Hayabusa (55 cm x 55 cm x 63 cm), and JAXA successfully launched it with Hayabusa 2 [2]. Currently, JAXA is in the final stages of launch preparation for the CubeSat "EQUULEUS" (6U size), which aims to travel to the Earth-Moon Lagrange point, and "OMOTENASHI" (6U size), which aims to achieve a lunar (crash-)landing [3].

Although NASA and JAXA have undertaken the aforementioned missions, there remains the problem that there are not many opportunities for their launch. The main reason is that deep space exploration missions of small satellites such as these are dependent on launch opportunities by large launch vehicles (Atlas rocket, SLS, H III, etc.) which already intend to leave Earth orbit. One of the ways to dramatically increase the opportunities for deep space exploration by small satellites is to take advantage of the opportunities to piggy back to common Earth orbits – which are in the midst of fierce market competition – and escape to deep space using a kick motor already mounted on the satellite. For example, if a small satellite is launched to a geostationary transfer orbit (GTO) and given an additional acceleration of about 700 m/s, it can be injected into a lunar orbit. To achieve this, a compact, low-cost, safe, and high-thrust kick motor is required.

Our team at Hokkaido University is leading development of such a kick motor, by taking advantage hybrid-chemical propulsion; hence the term, “Hybrid Kick Moto.” High-density polyethylene (HDPE, NFPA704: 0-0-0) is used as fuel, and nitrous oxide (N_2O, NFPA704: 2-0-0) is used as oxidizer, making it the safest high-thrust chemical propulsion system known to the authors. Since starting development in FY2017, the technology readiness level of the kick motor has increased from TRL 2 to TRL 5, and preparations are underway for achieving TRL 6 during FY2022 [4]. Screen captures of videos from one of the firing tests for achieving TRL-5 are shown in Fig. 1. Most functions of the kick motor up to TRL 6 can be performed on the ground using specialized equipment, however, the operation of the kick motor in microgravity requires minutes of free fall, and cannot be carried out within an aircraft or inside a space station. Nonetheless, on the path to achieving TRL 7, which will be defined as a successful transfer between non-intersection orbits – i.e. a Hohmann transfer – it is prudent to attempt to validate key functions of the kick motor in a space environment. Here, the term space environment means the combination of low pressure (less than 0.01 Atm) and weightlessness. This paper summarizes a proposal for using a sounding rocket experiment to accomplish this validation.



a) view from fore-end b) view from aft-end

Fig. 1 Screen captures of thrust measurement test for achieving TRL-5

2. Experiment Overview

The main objective of conducting the sounding rocket experiment is to validate the thrust performance of the Hokkaido University kick motor in a space environment without accruing the high cost of launching a flight model kick motor into Earth orbit. The main reason that a space flight is needed for the validation of the kick motor is that recreating the space environment on the ground for the amount of time necessary – at least a few minutes – is not feasible. The main challenge being the creation of weightless. Since the Hokkaido University kick motor will use saturated N_2O as the oxidizer, measuring the effect of the behavior of the liquid and vapor portions of the oxidizer during flight are of primary concern. Also, the behavior of the ignition method and flight stability are also of importance. Thus, the success criteria of the proposed sounding rocket experiment can be summarized as follows in Table 1 below.

Table 1　Summary of Experimental Objectives and Evaluation Criteria

Success Level	Description	Evaluation Method	Equipment
Minimum	achieve desired thrust	Confirmation that the target chamber pressure is obtained, and combustion oscillations are within acceptable limits by analyzing chamber pressure history.	See Fig. 2
Full	achieve reignition		
Advanced	capture burns on video	Replay digital video (e.g., GoPro) of nozzle exhaust gas with the earth in the background.	

2.1. Experimental Apparatus

The experimental apparatus is a hybrid (-chemical) rocket motor constructed from four pressure vessels for oxidizer storage, a combustor for plastic fuel and nozzle installation, and a fluidic system for controlling the supply of oxidizer to the combustor. A diagram of key components is shown in Fig. 2. The main concern of the oxidizer storage and fluidic system is to safely store N_2O up to launch operations, and then accurately control its flowrate during flight operations. Note, (saturated) liquid N_2O itself is completely non-explosive, non-flammable, and non-toxic, which is one reason it is widely available for commercial use. However, the critical temperature of N_2O (36 °C) is often lower than that of the daytime highs of Japan's launch facilities (~40 °C), meaning that some precautions must be taken to ensure that the pressure increase that results from a temperature increase is not large enough to cause a structure failure of the oxidizer storage and fluidic systems. The first precaution that is taken is the installation of redundant (pressure) relief valves, which will vent N_2O when it reaches the critical temperature. This venting measure is common to ground storage operations. The second precaution is the selection of high pressure-rated vessels and fluidic system components. All components will be rated to above 20 MPa, which is the pressure of supercritical N_2O when stored at 550 kg/m^3 and 90 °C [5].

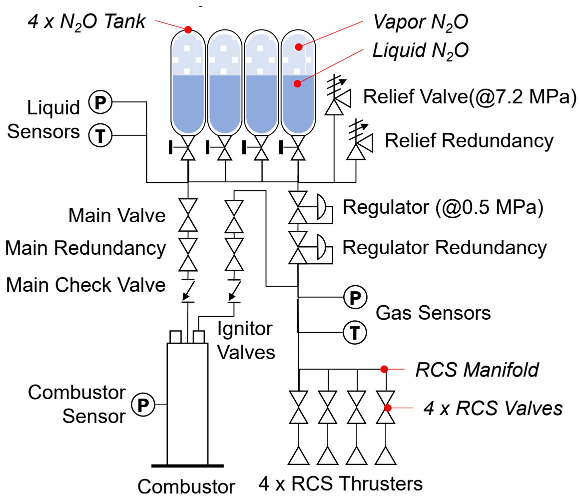


Fig. 2　System diagram

To confirm the thrust performance of the kick motor for the evaluation of success level, as well as for ensuring the safety of the experiment team, a minimum of three pressure measurements and two temperature measurements must be taken with a sampling rate of 10 Hz or more. These measurements are summarized in Table 2 below.

Table 2　Summary of Essential Measurement Data (Sampling Rate 10 Hz or more)

Measurement	Unit	Necessity
Liquid Pressure	MPa	Monitor the storage conditions of N_2O for property safety management. Check flow conditions during kick
Liquid Temperature	℃	
Gas Pressure	MPa	Monitor the storage conditions of N_2O for property safety management. Check flow conditions during pre-kick acceleration
Gas Temperature	℃	
Combustion Pressure	MPa	Evaluate thrust during kick

2.2. Experimental Sequence

A graphic depiction of the experiment and operation sequence is shown in Fig. 3. The experiment consists of three major phases of operation: (1) launch and payload separation; (2) kick motor operation; (3) data recovery and analysis. Within phase (1), which is carried out by the sounding rocket host team, the kick motor will be delivered in to a sub-orbital trajectory, and spin-stabilized to 1~3 Hz. Within phase (2), the kick motor team aims to achieve the "full success" criteria by performing two independent "kicks" and relaying the data back to the ground station. Within phase (3), efforts will be made to physically recover a data storage device from a sea landing, which will lead to "advanced succuss."

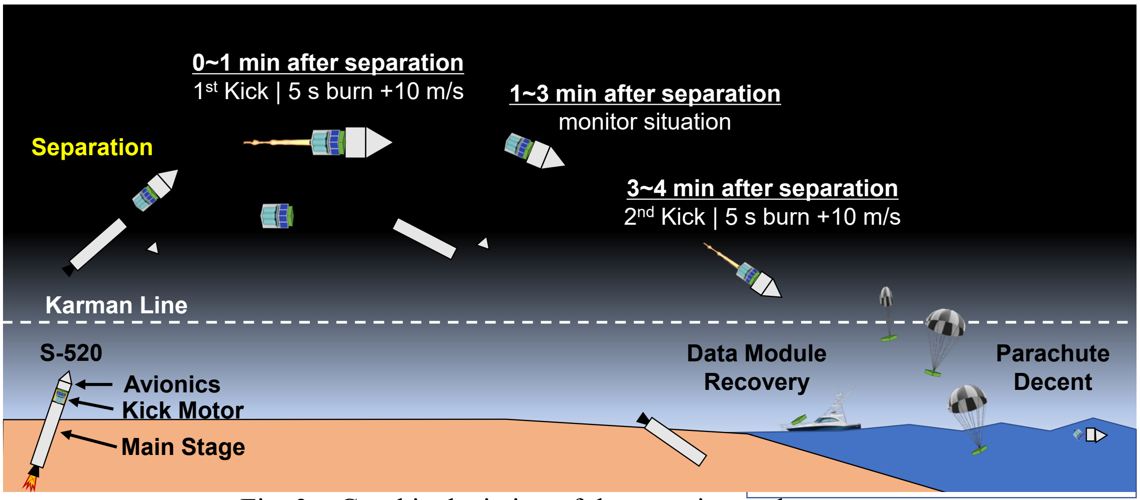


Fig. 3 Graphic depiction of the experimental sequence

3. Concluding Remarks

Over the past few years, the authors have been developing a hybrid (-chemical) rocket-based kick motor for small satellites. This kick motor overcomes the main drawback of existing chemical kick motors, which is the use of hazardous propellants. Most functions of the kick motor will reach TRL-6 this year through ground-based testing. However, some functions cannot be tested in full using ground-based equipment because the phenomena of weightless cannot be reproduced for long enough durations. Moreover, launching the kick motor into Earth orbit for testing is expensive and time-consuming. For this reason, the authors have proposed an experiment which uses the S-520 sounding for delivery and release into a sub-orbital trajectory above the Karman Line. The S-520 is powerful enough to delivery the kick motor to a height well above the Karman line, allowing for 5 min or so of freefall in "space." During this time the kick motor can test its primary function, producing multiple predictable and reliable "kicks" for dynamic orbital maneuvering. The thrust can be evaluated by measuring the chamber pressure history, minimizing the need for complex avionics. The results of this experiment will be essential for design of a flight model for future deep space exploration.

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