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高加速度環境を実現するロケットスレッドの走行プロファイル決定

Determining the Running Profile of Rocket Sled to Achieve High-Acceleration Environment

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Rocket sled systems enable researchers to conduct full-scale experiments under high-acceleration conditions, which is difficult to attain with any other system. Muroran Institute of Technology's High Speed Test Track in Shiraoi, Hokkaido, is the only academic rocket sled facility in Japan and the only rocket sled facility in the world to be propelled by hybrid rockets. However, with its 300-meter length, margin of error is slim, especially as braking relies on water braking system, which is set before the experiment and cannot be changed immediately. Thus, simulation of the running profile accurately is required. In this paper, we describe our homegrown software, the Sled Motion Analysis Tool, which enables simulation of rocket sled running profile. The software is mainly used for parameter tuning, which depends on past experiments. However, challenges remain, especially to improve simulations accuracy. Thus, various improvements, such as new sensor system, sensor fusion system, and other hardware improvements have been implemented. With the rocket sled system, from fiscal year 2023 onwards we have conducted various mission types ranging from 1.5 G to 3 G of peak recorded acceleration. In the future, more improvements are being planned to increase data reliability and increase accuracy of simulations.

Keywords: rocket sleds, dynamic simulations, hybrid rocket

1. Introduction

Rocket sleds testing has been conducted since the 1960's by the United States due to their unique testing characteristics; they allow full-scale testing, larger than wind-tunnel models, they are simpler than in-flight testing and often much cheaper, in addition, they also allow destructive testing if needed. Rocket sleds can be described as the middle ground between wind tunnel testing and in-flight test[1)]

Realizing this, Muroran Institute of Technology constructed a High-Speed Test Track (HSTT) for rocket sled experiments, which finished construction in October 2009. This facility, located in Shiraoi, Hokkaido, Japan, has a length of 300 meters, with international standard gauge (1435 mm). Hybrid rocket was selected as the propulsion system as it can be handled safely (as the sled would be operated by students), require no permission to operate, cost-effective, and its performance is adequate for rocket sled use case[2)]

Figure 1. Construction of High-Speed Test Track in Shiraoi, Hokkaido. [3)]

Figure 2. Launch of Run 60 (2023).

Figure 3. Cluster of two 5-kN class internally developed hybrid motor during launch. (2024)

Before each experiment, a simulation of the experiment is necessary to determine performance and safety of operation. As this is a unique case, simulation is done with internally developed tool called the Sled Motion Analysis Tool, or SMAT for short. This tool was first developed in 2009, and has received continuous update and development, with the latest version written in Python. [3)]

2. The water brake system

To stop the rocket sled, instead of a conventional braking system, a water brake system is used. In this water brake system, braking is achieved through momentum exchange between the sled and a static pool of water. On the sled, a bucket or other recovery device is installed, and upon entering the braking phase, this bucket would hit the static water, and as a result, will encounter significant resistance force from the water. [4)]

The momentum exchange between the sled and the water can be expressed using the following equation:

$$\begin{cases} m_{rocketsled} \cdot \vec{v}_{rocketsled} = m_{rocketsled} \cdot \vec{v}'_{rocketsled} + m_{water} \cdot \vec{v}'_{water} \\ \frac{1}{2} m_{rocketsled} \cdot v^2{}_{rocketsled} = \frac{1}{2} m_{rocketsled} \cdot v'^2{}_{rocketsled} + \frac{1}{2} m_{water} \cdot v'^2{}_{water} \end{cases} \quad (1)$$ [4)]

Where m is mass and v is velocity, respectively.

The braking force of water is a function of mass, however, as the geometry of the water channel remains unchanged along the entire length of the rail, mass of the water can be substituted by the height of the water inside the channel. Therefore, by varying the height of the water channel, we can control the brake force.

Figure 4. The water channel for water braking, located between the rails. By varying the height of the water gate, the braking force can be controlled.

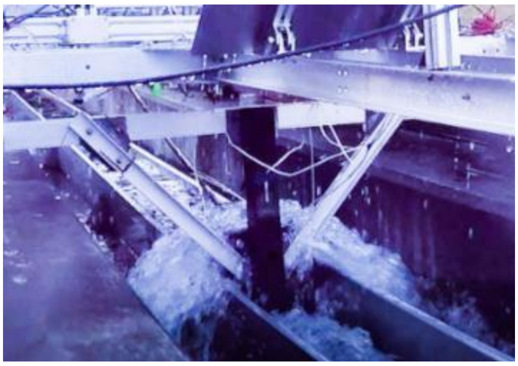


Figure 5. Close up of the water brake in action. (Run 49). [5]

Figure 6. Momentum exchange between the sled and the static water during braking.

3. Problem definition and challenges in rocket sled operation

Compared to other rocket sled facility in the world, Muroran Institute of Technology's High-Speed Test Track is comparably shorter [6]. As a consequence, the margin of error is slim, as insufficient braking force would result in sled overrun, while too much of a braking force will damage the sled and the payload.

Table 1. Examples of High-Speed Test Track around the world. [6]

Test Track Name	Location	Length (m)
Holloman High-speed Test Track 1 & 2	United States of America	15336
Martin-Baker Langford Lodge	United Kingdom	1890
Centre Dessais Des Landes R1	France	1200
Shiraoi High-speed Test Track	Japan	300

From the braking perspective, as the height of the water channel cannot be changed in short notice, it is important to analyze how much braking power is required. Finding the optimal balance between stress on the sled and being able to stop safety is a challenge. In addition to that, this braking force must be translated to height of the water channel.

From operational perspective, depending on the payload and the parameters on the day of the experiment (such as rail's friction coefficient, air temperature, actual rocket thrust value, etc.), every mission would have different profile, and no mission is the same. Situation can change rapidly, and previously calculated running profile and the required water height may not be applicable at the actual experiment.

4. Sled Motion Analysis Tool (SMAT)

As a result, it is of interest to the rocket sled experimenters to accurately simulate how the rocket sled would behave before the experiment. Various techniques and algorithms have been used to simulate the rocket sled running profile.[7)]

Because rocket sled is a niche subject, there is currently no commercial software to simulate rocket sled running profile. Thus, Muroran Institute of Technology utilizes an internally developed rocket sled running profile simulator called Sled Motion Analysis Tool (SMAT). SMAT has been in development since the beginning of the rocket sled program in 2010.[8)]

At the moment, the Sled Motion Analysis Tool is on Version 3.7, and is written in Python.

The Sled Motion Analysis Tool is mainly used for multi-case analysis; as the height of the water channel cannot easily be changed, it is important that the set height can be sufficient for a range of scenarios, such as variation in rocket thrust (due to changing air temperature, as the propellant tank is self-pressurized) , and variation in friction (such as rail friction due to being wet because of rain, etc.)

In addition, the Sled Motion Analysis Tool can take into account mission specific analysis, such as parachute deployment. During parachute deployment run, additional drag from the parachute must be considered in the running profile simulation.

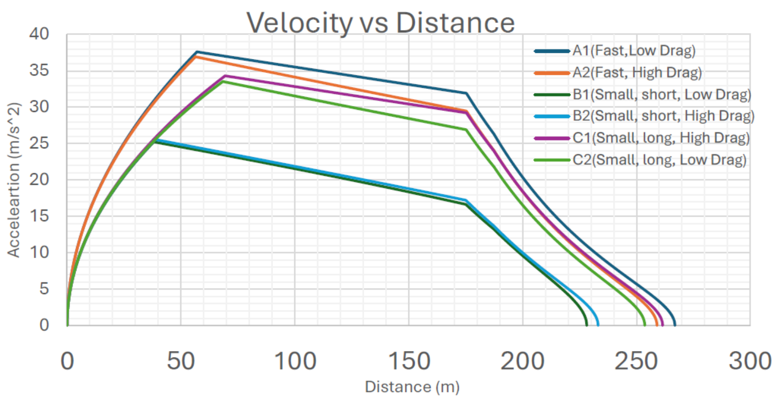
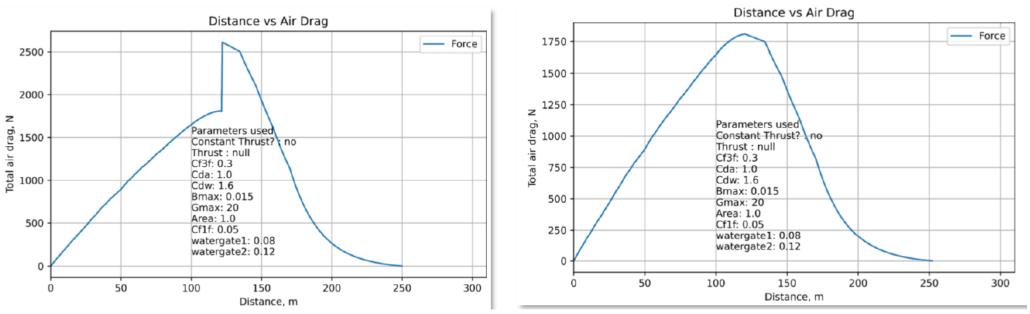


Figure 7. Example of multi-case analysis showing different running profile at the same water gate height.



(a) (b)

Figure 8. Effect of parachute deployment on air drag. (a) with parachute. (b) without parachute.

5. The SMAT workflow

The SMAT program is usually as a tool for parameter tuning. The parameter tuning methodology can be explained as follows:

1. Pre-run Simulations: based on previous knowledge and the estimated parameters of the next run, some pre-run simulations were conducted. At this stage, the main objective is to ensure safe braking.
2. Launch of the rocket sled: the experiment is conducted and as much data as possible is gathered.
3. Post-run simulations: based on data of the actual run, we reverse-engineer the results in our simulations. Parameters are tweaked until our simulation results match the actual running profile.
4. Data analysis and improvement for the next run: results of the post-run and actual run is then combined and analyzed. Reason why the sled behave that way is investigated. The results of the analysis are then fed again in the next pre-run, with the aim of increasing accuracy.

6. Accuracy of SMAT software

At the moment, the accuracy of the SMAT software can be explained through the following graph:

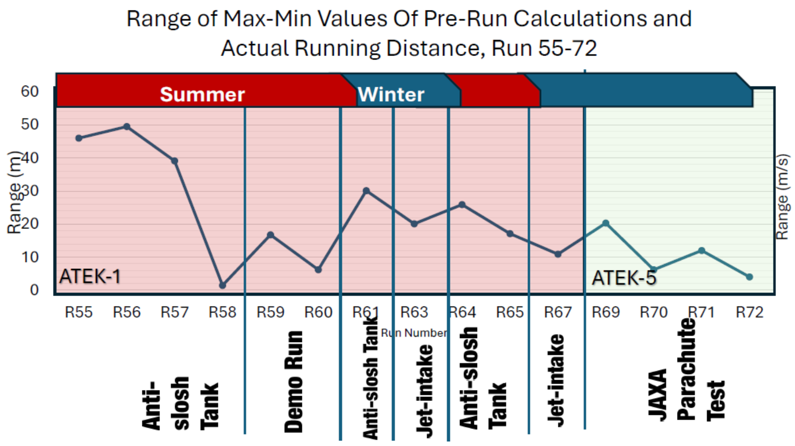


Figure 9. The range of pre-runs prediction of rocket sled and actual running distance over time.

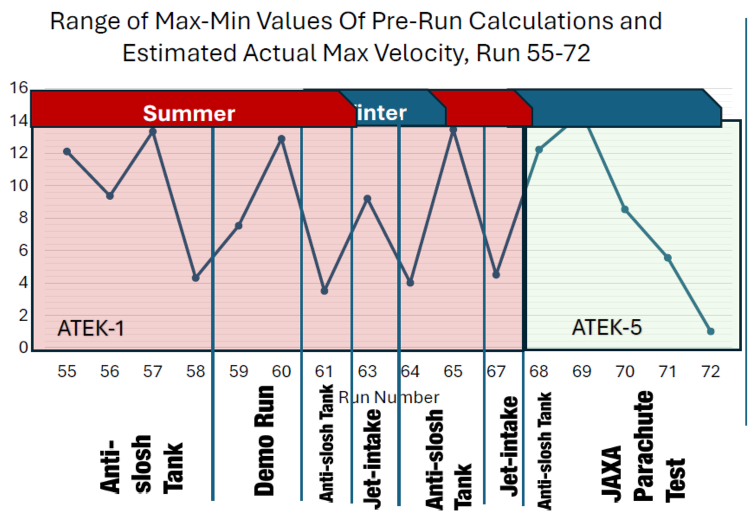


Figure 10. The range of pre-run predictions and actual recorded maximum velocity over time.

Legend: ATEK-1 launches were propelled by 4 units of 1-kN class hybrid motors. ATEK-5 launches were propelled by 2 units of 5-kN class hybrid motors.

As seen from Figure 9, the range of pre-run predictions and actual running distance over time decreases, showing increasing accuracy and confidence in the prediction of total running distance. However, in Figure 10, this effect is not observed.

This shows that while we are able to increase our accuracy and confidence in estimating total running distance, this is not the case for our prediction of maximum velocity of the sled.

7. Challenges in Increasing Accuracy

The main challenge in increasing the accuracy of maximum velocity prediction is the data for analysis itself is often conflicting with each other or not reliable, making analysis difficult. This makes the prediction quality go down as well.

In addition, as explained above, calculated pre-run variables and the variables encountered during the actual day of the experiment might differ. As a result, the pre-run results are actually not applicable for the day of the experiment. Such example is the difference in rocket thrusts value. Due to difference in air temperature, the pressure in the tank is lower than expected, and thrust value might differ significantly from the pre-run value. As a result, the sled is slower than simulated.

8. Efforts in Improving Accuracy of SMAT

o mitigate the two problems above, efforts have been made, which will be explained below:

8.1. New Sensor System (Gap Sensor)

Up until now, for velocity measurement, we rely on two sensors, which are the pressure differential sensor (obtaining velocity through comparison of a pitot tube and a static port) and accelerometer (by integration of acceleration). This data might not agree with each other and give different values. As such, an additional sensor was installed. This gap sensor (Figure 11) would give a signal upon detecting aluminum channels that were placed along the track (Figure 12 & 13). As the spacing of the aluminum channel and timestamp is known, velocity can be calculated.

Figure 11. The gap sensor, installed on the sled.

Figure 12. Aluminum channels (30 cm long) were placed beside the rails at 3 meters interval.

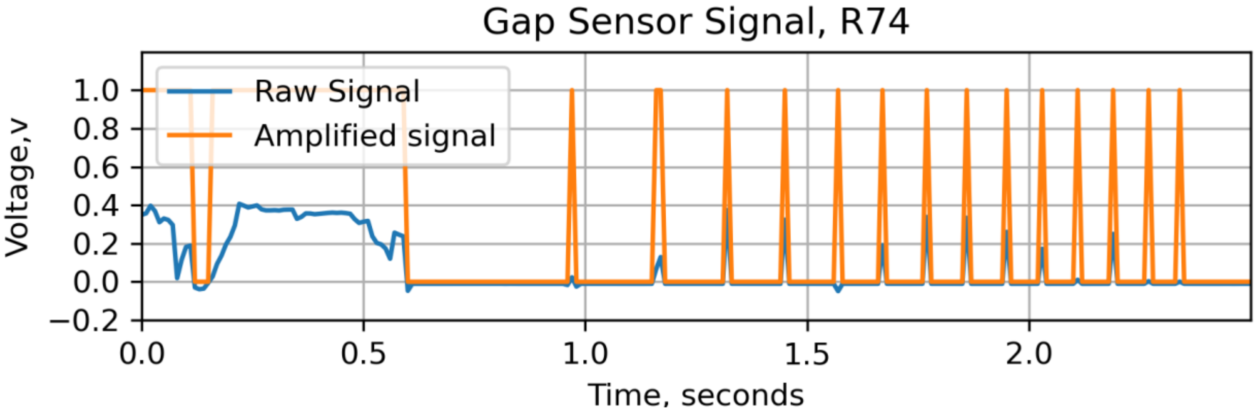


Figure 13. Response of the gap sensor, showing as the sled goes faster the time between aluminum channels decreases.

8.2. Sensor Fusion

With multiple sensors available, using filters such as Kalman filtering we can combine the data into a single value. A basic implementation of predict-update algorithm was done to combine velocity data from the accelerometer and the result from gap sensor.

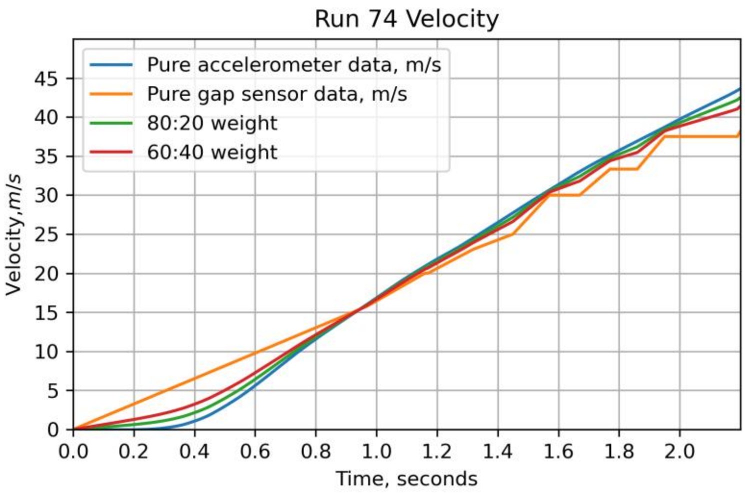


Figure 14. Result of combining velocity data obtained from the accelerometer and the gap sensor through basic predict-update weighted average algorithm of Run 74.

8.3. Hardware Improvements

Besides software improvements, some hardware improvements were also made to increase the reliability of the entire system itself.

8.3.1. Tank Heating

As previously mentioned, with self-pressurized system, rocket thrust is a function of ambient air temperature. During winter, as ambient temperature falls, so is the rocket thrust. As a result, the rocket sled team implemented a tank heating system, which heats the tank, raises the tank pressure and therefore increases rocket thrust. With this system, we were able to keep the rocket thrust the same whether it is conducted in summer or in winter.

Figure 15. The tank heating system, implemented since Run 68.

8.3.2. Pitot tube improvements

With disagreement between the differential pressure and the accelerometer values, for Run 74 the location of the differential pressure was changed. Previously, the distance between the pitot tube and the sensor was around 4 meters, but we cut it down into around 30 cm.

9. Accomplished Mission Types (2023~)

Since the resumption of rocket sled activity in 2023, in total four mission types have been conducted, each with varying requirements.

9.1.1. Anti-sloshing tank

An anti-sloshing tank is a tank that prevents sloshing of liquid under various accelerated conditions, and so maintaining constant acceleration is the goal of the rocket sled experiment. In total, eleven runs have been conducted from 2023 onwards to test the anti-sloshing tank. As the payload mass is heavy, high acceleration was not possible, and most of the experiment was conducted in 1G accelerated environment.

Figure 16. Anti-sloshing tank experiment.

9.1.2. Parachute deployment

In December 2024, joint research with JAXA was conducted, with the main goal of verifying operation of a parachute system for a return capsule. In total, four runs were conducted. Recorded maximum acceleration was around 2 G.

Figure 17. Parachute deployment test. (2024)

9.1.3. Jet intake

Mission requirement for jet intake testing does not stipulate the needs for high acceleration, but rather high peak velocity. However, due to the light weight of the payload, maximum acceleration (and velocity) was attained with this payload. Maximum recorded acceleration was around 3G.

Figure 18. Jet intake test

9.1.4. Demonstration for the public

In addition to scientific payload, as a unique facility in Japan, we also conduct demonstration run for members of the public. Due to the hybrid motor configuration (4*1-kN class motors), despite the light weight, high acceleration was not attained. Maximum recorded acceleration was 1.5 G.

Figure 19. Demonstration for the public. (2023)

10. Further research

In the future, we are exploring the possibility of integrating GPS systems into our data collection process. This is spurred by recent developments in GPS technology that allows high speed location acquisition in an affordable package.

Further detailed error analysis will be conducted to precisely determine the error and accuracy of all relevant sensor systems. In addition, a more comprehensive Kalman filtering algorithm will be developed that will be able to combine not just two sensors, but all four available sensors (GPS included) to obtain more accurate data. This data would then help to increase the accuracy of parameter tuning of SMAT.

11. Conclusion

Muroran Institute of Technology operates the only academic rocket sled facility in Japan, which necessitates the use of an internally developed simulation tool called Sled Motion Analysis Tool, to determine how the rocket sled would launch. The accuracy of this tool is vital to realize high-acceleration experiments in a safe manner. However, as the software is used as a means of parameter tuning, its accuracy depends on the quality of the data of previous experiments, which might be difficult to acquire. Improvements in both hardware and software have been made. Various mission types at high acceleration between 1-3 G have been conducted successfully. Increasing accuracy is still a priority in the future.

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