DEVELOPMENT STATUS OF LASER-INITIATED FLIGHT TERMINATION SYSTEM

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ABSTRACT:

In Japanese space development, electrical initiation has long been used for all pyrotechnics on solid rockets. Although extensive qualification tests and strict manufacturing control have ensured high reliability, bridge-wire electro-explosive devices inherently retain a risk of inadvertent ignition from electrical disturbances or stray currents, requiring stringent safety measures at launch sites. To achieve higher safety, IHI Aerospace is developing laser-initiated ignition systems (LIISs) to progressively replace electrical initiation for solid motor ignition, separation devices, and flight termination systems (FTSs). This study develops a laser-initiated FTS for solid rocket motors that eliminates electrical risks by transmitting laser energy through optical fibers. A ring-shaped linear shaped charge (LSC), processed from a LSC with extensive flight heritage on H-series launch vehicles, is adopted as the explosive of FTS. Penetration tests, optical fiber routing evaluations, environmental tests, and full-scale CFRP motor case rupture tests confirm the practicality and reliability of the laser-initiated FTS.

1. INTRODUCTION

The flight termination system (FTS) installed on solid rocket motors is a critical system designed to ensure safety in the areas surrounding the flight corridor by reliably destroying the vehicle when an anomaly is detected during rocket flight. A typical flight termination procedure is as follows: telemetry data transmitted from the rocket in flight to the ground are continuously monitored. If the rocket significantly deviates from the planned flight trajectory and it becomes unlikely that safety can be maintained, or if mission success is determined to be impossible, a destruct command is transmitted from the ground to the rocket. Upon receipt of the destruct command onboard the rocket, the ignition charge incorporated in the FTS is activated, and the resulting flame sequentially propagates through multiple explosive trains, ultimately initiating a linear shaped charge (LSC). This process ruptures the rocket motor combustion chamber and terminates thrust generation. The FTS is required to exhibit extremely high reliability, ensuring operation at the precise required timing. At the same time, it is essential to prevent unintended activation (inadvertent ignition). In Japanese rockets, electro-explosive devices (EEDs) have been employed as the ignition method for FTSs and for ignition charges in solid motor ignition systems for over 40 years, demonstrating high reliability under stringent operational constraints. However, EEDs function by igniting the charge via Joule heating generated through the passage of electric current in a lead wire in contact with the ignition charge. The risk of inadvertent ignition due to electrical disturbances—such as electrostatic discharge during assembly operations, electromagnetic induction, or stray currents associated with lightning—cannot be entirely eliminated. Therefore, to further enhance the reliability of solid rockets beyond the current level, it is essential to adopt an ignition method that provides higher reliability than EEDs.

In this study, a laser-initiated ignition system (LIIS) was adopted as the ignition mechanism for the FTS, serving as an alternative to the conventional electrical initiation method. In LIIS, laser light provides the energy required for ignition, and an optical fiber cable is used as the energy transmission path to the ignition charge. This configuration eliminates the risk of electrical disturbances being transmitted to the ignition charge and, consequently, prevents inadvertent ignition [1,2]. Furthermore, LIIS is applicable to solid rocket motor ignition. This paper presents an overview of the development of an FTS that employs LIIS as its ignition device.

2. LASER-INITIATED IGNITION SYSTEM (LIIS)

2.1. Ignition System

The ignition system of a solid rocket motor must ensure safety at launch and reliable operation. In conventional Japanese solid rockets, ignition systems have employed combinations of pyrotechnic trains comprising an ignition charge initiated by an EED together with pyrotechnic devices such as through-bulkhead initiators (TBI) and confined detonating fuses (CDFs). These devices were put into practical use only after extensive qualification testing, and a large body of operational experience has been accumulated. Among the pyrotechnic trains used for motor ignition, the TBI, which places explosives on both sides of a bulkhead and transmits the upstream detonation signal to the downstream side through the bulkhead, functions as the trigger of the solid rocket motor (SRM) ignition system. At the same time, it prevents pressure leakage by means of the metallic bulkhead and ensures a high level of safety with respect to electromagnetic compatibility (EMC). Thus, its continued use will remain indispensable.

In a conventional EED, an electrical bridge-wire is in contact with the ignition charge, and the required energy is released through the bridge-wire, thereby inducing a rapid chemical reaction in the ignition charge. Because the bridge-wire is in contact with the ignition charge, even a small current flowing through it results in heat energy being input to the ignition charge. Therefore, the risk of inadvertent initiation due to electrical disturbances or electrostatic discharge cannot be completely ruled out for EEDs. Since the ignition charge has a certain sensitivity to the energy required for ignition, strict safety measures are enforced at rocket launch sites to reduce the possibility of inadvertent initiation as much as possible. To enhance the reliability of the ignition system with respect to safety beyond that of EEDs, it is necessary to adopt a method in which the bridge-wire is not in contact with the ignition charge.

LIIS intrinsically avoids the risk of inadvertent initiation due to electrical disturbances by using a non-conductive optical fiber cable (OFC) to achieve complete electrical isolation between the laser firing unit (LFU), which is the source of the ignition energy, and the ignition charge initiated by the laser beam. This paper describes a system that employs a laser-initiated detonator (LID) as the head element of the pyrotechnic train for motor ignition and for the FTS.

2.2. LID

An overview of the LID is shown in Fig. 1. An SMA905 connector has been selected as the optical fiber connection interface, and the opposite end is designed to deliver energy to the ignition charge through an acrylic window. By sealing the surroundings of the ignition charge such that only light can reach it as ignition energy, electrical influences from the external environment are shut out. Since laser light can be focused onto an extremely small area to apply high energy to the ignition charge, an ignition charge with lower sensitivity than that used in EEDs can be employed, thereby improving safety. The ignition charge is sealed by a sealing material that is thin enough to be reliably ruptured by the high-temperature, high-pressure gas generated during operation, while having sufficient strength to remain stable under various environmental conditions. Furthermore, the optical fiber incorporated within the LID is completely sealed by a hermetic structure, resulting in a robust configuration capable of withstanding severe environments such as vibration and shock expected during flight. Through such a design, LIIS achieves a level of safety and reliability that is difficult to attain with conventional electrical ignition methods, and it also contributes to increased design flexibility of ignition systems and to the reduction of operational costs [3].

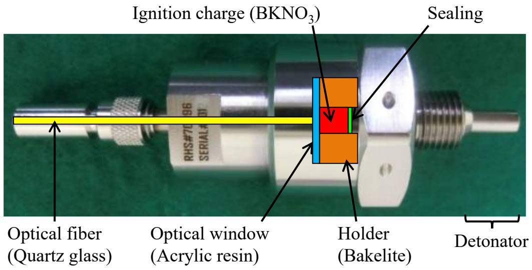

Figure 1. Schematic diagram of LID.

3. RING SHAPED LSC

In conventional Japanese rockets, the FTS is configured such that initiation by an EED triggers a linear shaped charge (LSC) via a CDF. In contrast, in an FTS employing LIIS, the function of the CDF is replaced by a combination of an OFC and an LID (Fig. 2).

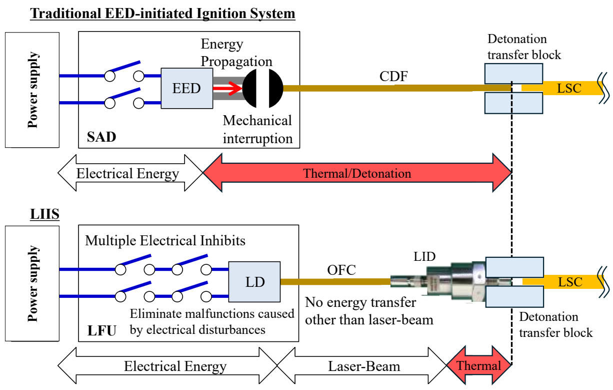

Figure 2. Differences in energy transfer systems.

In this development, a linear shaped charge (LSC) that has been mounted for many years on Japanese large H-series rockets and has extensive flight heritage was processed into a ring shape (diameter approximately 800 mm) for installation on a small solid rocket and was mounted on the dome structure of the solid motor. The ring-shaped LSC, which is produced solely by bending the existing LSC, can leverage the reliability that has been flight-proven with the existing LSC, thereby enabling a substantial reduction in the scope of qualification testing. In this development, additional qualification tests for use as a ring-shaped LSC (temperature and humidity, vibration, and shock tests) were conducted.

Due to the nature of bending an existing LSC, the ring-shaped LSC has two end sections along the circumference. By attaching LIDs to both end sections via detonation transfer blocks, a redundant configuration is realized with respect to initiation. In addition, the two ends are designed to overlap along the circumference, providing the function of creating a large opening in the motor case dome upon actuation. This configuration makes it possible to interrupt the thrust of the solid rocket motor while keeping the required installation volume small (Fig. 3).

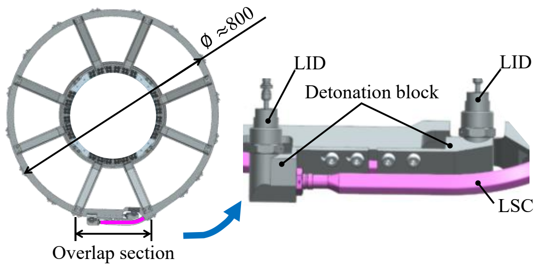

Figure 3. Schematic diagram of ring-shaped LSC.

4. OFC ROUTING

As in conventional FTSs, where the EED and LSC are connected by a CDF, in LIIS the LFU and LID are connected by an OFC. Both the CDF and OFC are routed with various lengths depending on the rocket structure. For OFC routing, it is naturally necessary to define operational constraints on bending and related factors that differ from those for conventional electrical wiring and CDF routing. Therefore, evaluations required for routing design were conducted.

Bending inevitably occurs in the routing of cables. In the case of an OFC, to keep attenuation of laser output due to bending within an acceptable range, routing criteria for the minimum bend radius and the number of bends must be established. Regarding the minimum bend radius, a radius of 30 mm, recommended in ITU-T standards, was adopted, and the margin of transmitted laser energy was verified with the bend radius and the number of bends as parameters.

The test setup is shown in Fig. 4. In this test, the effect of bending on output attenuation was evaluated by measuring, with a joulemeter, the laser beam emitted from the LFU while the OFC was wound multiple times around pipes of various diameters. Prior to evaluating output attenuation, the system requirements for LIIS were organized. First, a minimum guaranteed output of 10 mJ was specified for the LFU as a product, such that a margin of several times can be achieved relative to the laser output required to satisfy the 99.9999% firing condition of the LID [4]. In this test, verification was carried out using an LFU with a minimum output of approximately 13 mJ. To verify the number of OFC bends under conditions exceeding those anticipated in normal routing, attenuation of the laser beam was evaluated assuming up to 19 bends.

The test results are shown in Fig. 5. Laser output was measured and plotted for each bend radius and number of bends. Data points marked with circles indicate that the measured laser output meets the minimum guaranteed output. The graph shows that the smaller the bend radius and the greater the number of bends, the larger the attenuation of laser output. It is also evident that the smaller the bend radius, the greater the effect of the number of bends on attenuation. For a bend radius of 30 mm, the difference in output between 1 bend and 19 bends is only about 2.4%, indicating that sufficient margin with respect to the system requirement is maintained regardless of the number of bends. In addition, for a bend radius of 15 mm, the output satisfies the system requirement even with 19 bends. For a bend radius of 10 mm, the system requirement can no longer be satisfied for 10 or more bends, and it is therefore considered unsuitable for practical use.

From the above, it was confirmed that, by constraining the routing to a bend radius of 30 mm, the LID ignition function is not impaired even when multiple bends occur.

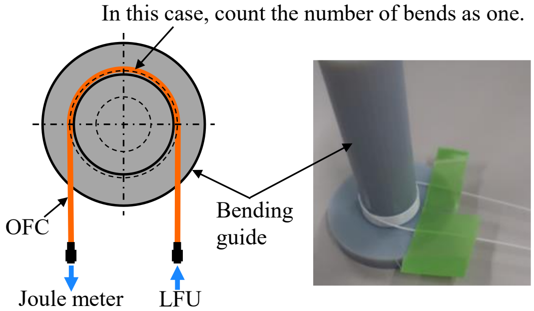

Figure 4. Bending test setup.

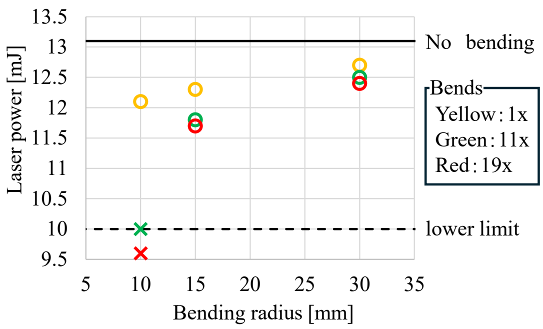

Figure 5. Bending Test Results.

During routing, care must be taken not to apply excessive bending or twisting to the OFC to avoid fiber breakage. On the other hand, slight twisting of cables in routing cannot be avoided, and in general a maximum twist of about half a turn (180°) is anticipated. In the setup shown in Fig. 6, the optical fiber is connected to the LFU and the joulemeter. While maintaining this configuration, the joulemeter was rotated in 90° increments, thereby introducing twist into a 2 m OFC, and the laser output was measured to evaluate the effect of twisting. Even when a twist of 15 turns (5400°) was applied, no significant attenuation of laser output was observed. Because the effect of twisting depends on the OFC length, the twist angle was converted to that corresponding to the maximum fixed interval of 300 mm assumed in actual routing. From the ratio of OFC length (300 mm / 2000 mm), 15 turns correspond to 2.25 turns (810°). It was thus confirmed that there is more than a fourfold margin relative to the twist angles typically assumed in electrical cable routing.

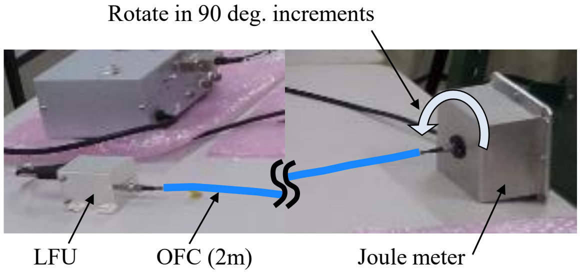

Figure 6. Torsion test setup.

To verify the feasibility of the overall system, a QT-level random vibration test was conducted using the assembled FTS configuration. A dummy ring-shaped LSC was employed, and the LFU and other components were mounted in a configuration representative of installation on a small satellite launch solid rocket, with the OFC routed accordingly. The laser energy transmitted from the LFU through the OFC was measured with a joulemeter before, during, and after the vibration exposure, and the energy difference relative to the pre-vibration condition was evaluated. No significant change in laser output was observed during or after the vibration loading, demonstrating that system integrity was maintained. Based on these results, the integrity of the energy transmission line of the laser-initiated FTS and the effectiveness of the routing method were verified.

5. QUALIFICATION TESTS

Qualification tests for the ring-shaped LSC were conducted as part of the laser-initiated FTS.
In these tests, after applying environmental conditions that cover the period from storage through launch, the performance was evaluated by means of firing tests.

5.1. Temperature and Humidity Cycling Test

The temperature range was set from -10°C to +80°C. The humidity condition was set to over 90% relative humidity at +80°C, and the number of cycles was set to 10, as shown in Fig. 7.

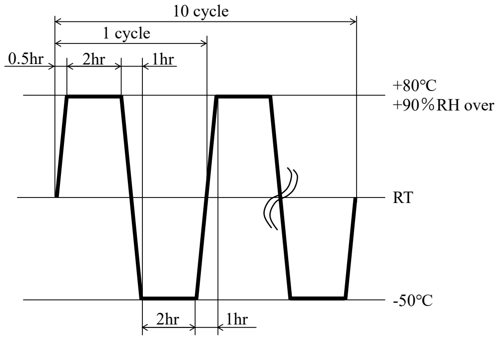

Figure 7. Temperature and humidity cycle test conditions.

5.2. Vibration and Shock Test

The vibration and shock test setup is shown in Fig. 8, and the test conditions are shown in Fig. 9. The test conditions were based on the environmental conditions defined for the interface between the FTS adapter for the previously described small solid rocket and its rocket motor, and the ring-shaped LSC was vibrated in combination with the adapter. Post-test visual and X-ray inspections confirmed that no damage had occurred to the LSC.

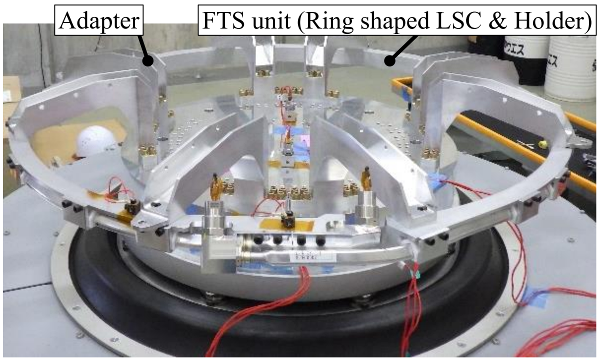

Figure 8. Vibration and shock test setup.

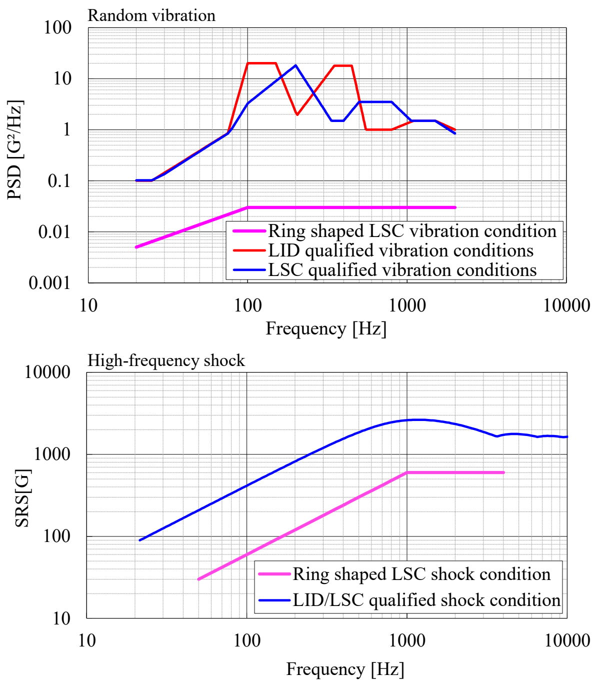

Figure 9. Vibration and shock test conditions.

5.3. Firing Tests (Penetration Depth)

From the standpoint of its operating principle, the LSC must be positioned at an appropriate distance from the object to be cut [5,6]. This distance is called the standoff distance, and the basic characteristics for a straight configuration had already been obtained at the time of the original LSC development (dashed line in Fig. 12). In this study, considering the additional bending to form the ring shape, verification by firing tests was conducted from the following viewpoints:

a. Penetration at minimum bend radius
b. Effect of bending on penetration

a. Penetration at minimum bend radius

Near the overlap section of the ring-shaped LSC, the bend radius is smaller than in the general sections due to forming constraints, raising concerns about a possible reduction in capability. For the overlap section, the standoff distance was treated as a parameter within the design range (30 mm to 60 mm), and performance was evaluated. The LSC used in this test was a test specimen that reproduced the vicinity of the overlap section of the ring-shaped LSC, simulating a configuration close to the actual structure. This specimen was able to reproduce all geometrical elements of the ring-shaped LSC (straight section, R100 section, and R400 section). As targets, a CFRP plate (approximately 7 mm thick) and aluminum were used, and the penetration margin was evaluated by measuring the depth of penetration into the aluminum backup after cutting through the CFRP plate (Fig. 10).
As a result of the tests, although a reduction in penetration capability was observed in the R100 section, it was confirmed that penetration reliably reached the aluminum target under all standoff distance conditions. This demonstrated that there is sufficient margin for cutting the CFRP plate (Tab. 1). In addition, the data obtained under each test condition will provide useful insights for future design optimization and safety assessment.

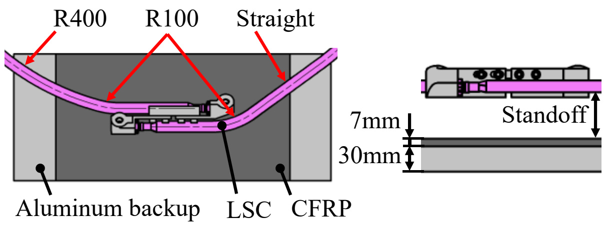

Figure 10. Partial component firing test setup.

Table 1. Penetration margin after CFRP cutting.

Standoff [mm]	Straight [mm]	R100 [mm]	R400 [mm]
30	10.2	8.9	11.0
55	7.2	4.3	8.1
60	6.7	3.3	6.7

b. Effect of bending on penetration

In the second test, a ring-shaped LSC was employed, with the standoff distance varied along the circumference to evaluate performance at each distance. The standoff distance ranged from 10 to 70 mm, corresponding to the range of data obtained during the development phase of the existing LSC, consisting of measuring the penetration depth into an aluminum plate to determine whether bending the LSC uniformly into a ring caused any reduction in penetration capability.
For the overlap section, the assumed LSC standoff distance was fixed, and a CFRP plate, the structural material of the solid rocket motor case that is assumed to be the cutting target, was installed to verify whether cutting could be achieved. In this case, the standoff distance was set to the design nominal value of 55 mm for the overlap section, and the CFRP plate (approximately 7 mm thick) was cut from the dome section of a small solid rocket motor case that had been separately manufactured on a trial basis, thereby simulating actual operational conditions (Fig. 11).
As a result of the test, in the regions with a bending radius of 400 mm, excluding the overlap section, performance comparable to that obtained with the existing LSC was confirmed (Fig. 12). In other words, it was demonstrated that the ring-shaped LSC has penetration capability equivalent to that of a conventional straight LSC.
With respect to the overlap section, the CFRP plate was reliably severed, and clear penetration into the aluminum backup placed behind it was also observed, confirming that there is sufficient margin for cutting the CFRP combustion chamber of a solid rocket motor.
Through these tests, it was shown that the penetration performance of the ring-shaped LSC is stably exhibited under various standoff distances and structural conditions, and it was confirmed that it possesses sufficient performance for application to actual rocket structural components.

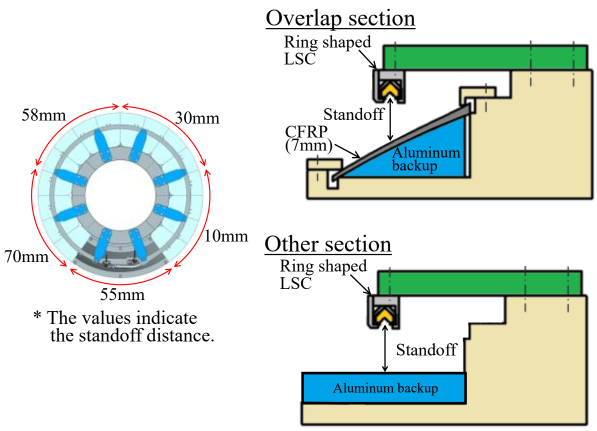

Figure 11. Ring shaped LSC firing test setup.

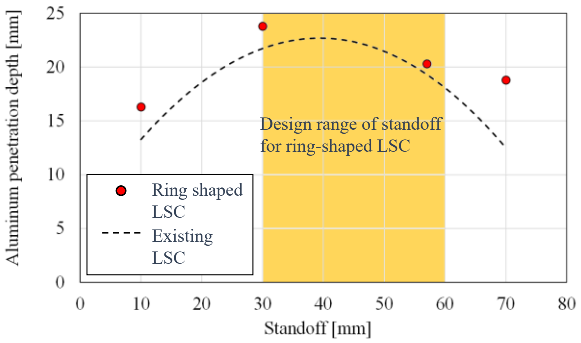

Figure 12. Penetration curve of ring-shaped LSC.

5.4. Firing Test (Motor Case Rupture)

To evaluate the performance of the ring-shaped LSC under conditions closer to an actual operational environment, a full-scale prototype motor case (outer diameter: approximately 1.4 m) for a solid rocket used to launch small satellites was employed, and a demonstration test was conducted in which the motor case was opened using the ring-shaped LSC. In this test, the LFU was mounted on the domed section of the motor case, and the LIIS (LFU, OFC, LID) was arranged in a configuration assuming actual operation to verify the functionality of the overall system. This allowed the initiation behavior and penetration performance of the ring-shaped LSC in a real rocket structure to be directly demonstrated. As a result of the demonstration test, both the CFRP motor case and the insulation arranged on its inner-diameter side were reliably severed. No issues were observed in the series of operations from initiation through cutting, thereby demonstrating the level of maturity of the overall system.

6. IN-FLIGHT DEMONSTRATION

The LIIS and ring-shaped LSC developed in this study were installed on a Japanese small satellite launch vehicle and used in an actual flight in 2026. This achievement is an important demonstration of the practicality and reliability of laser initiation technology and the ring-shaped LSC and is expected to contribute significantly to the future advancement of rocket safety technologies.

7. CONCLUSION

In this study, the LIIS and the ring-shaped LSC were developed and evaluated as an FTS for solid rocket motors. For the LIIS, performance verification was conducted under conditions that simulated actual flight configurations, including bending and twisting of the OFC and vibration. The stability of laser energy transmission and reliable operation were confirmed, demonstrating that the LIIS has sufficient reliability even in environments assumed for actual operation.
The ring-shaped LSC was developed based on the original LSC, thereby reducing the number of qualification items while demonstrating high penetration performance and reliable functioning. The results of various tests clarified that the ring-shaped LSC has sufficient penetration capability against CFRP and aluminum and can reliably cut the motor case.
Through flight demonstration on a small satellite launch vehicle, the practicality and reliability of this system were verified. These achievements are expected to contribute significantly to the future development of safety technologies for solid rockets.

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