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Recent Developments of Experimental Winged Rocket: Autonomous Guidance and Control Demonstration Using Parafoil

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Abstract

Since 2005, Space system laboratory of Kyushu Institute of Technology has been studying experimental unmanned rockets called WIRES (WInged REusable Sounding rocket) [1-3]. WIRES are test beds and demonstration platforms for future reusable space transportation system to reduce space transportation cost. In this paper, design, development, ground combustion test and flight test of the winged rocket named WIRES#012IA are presented. WIRES#012IA aims to demonstrate autonomous guidance and control using parafoil.

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1. Introduction

Since 2009, authors have been designing and developing two experimental rockets WIRES#012 and WIRES#014. WIRES#012 is a conventional rocket that has a total length of 1.7 m and initial weight of 34.3 kg. The objective of WIRES#012 is to validate CFRP (Carbon Fiber Reinforced Plastic) body structure and to demonstrate parachute recovery studied by authors. The engine of WIRES#012 is a commercial hybrid rocket motor HyperTEK M1000.

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The flight test was conducted in 2010, and the rocket reached the altitude of 764 m and was recovered on the ground with a little damage (Fig. 1) [4].

WIRES #014 is a winged rocket that has total length of 1.7 m and initial weight of 49.3 kg. The objective of WIRES#014 is to demonstrate guidance, navigation and control system and to conduct fully autonomous gliding flight [5]. The propulsion system of WIRES#014 employs a hybrid rocket motor CAMUI (CAscaded MULTistage Impinging-jet) developed by Hokkaido university [6]. The flight test was conducted in 2013 and the rocket reached the altitude of 596 m, but the gliding flight was not successful due to the failure of attitude control (Fig. 2). Ground operator commanded emergency recovery sequence and deceleration chute was deployed. However, the remaining altitude was not enough to open main parachute, and the rocket made a hard landing.



Fig. 1. Flight Experiment of WIRES#012.



Fig. 2. Flight Experiment of WIRES#014.

2. System of WIRES#012IA

2.1. Overview

After the successful demonstration of parachute recovery by WIRES#012, the authors designed WIRES#012IA to demonstrate the guided parafoil recovery. WIRES#012IA is a conventional shape rocket that performs autonomous guided parafoil flight to recover at a target point (Figs. 3 and 4). The fuselage of WIRES#012IA is almost the same as WIRES#012. WIRES#012IA has a total length of 1.7 m and has total weight of 40 kg (Table 1). The rocket is expected to reach the altitude of 1000 m. The parafoil has wing area of 4 m.



Fig. 3. WIRES#012IA



Fig. 4. Parafoil of WIRES#012IA

Table 1. Specifications of WIRES#012IA

Initial weight	40.0	[Kg]
Total length	1.7	[m]
Body diameter	0.33	[m]
Wing span of parafoil	4	[m]
Wing area of parafoil	6.96	[m ²]
Number of cells in parafoil	9 cells	[-]
Aspect ratio of parafoil	2.29	[-]

2.2. Avionics

The Fig. 5 shows the avionics of WIRES#012IA with the telemetry. The avionics system has five microcomputers. The GPS (Global Positioning System) microcomputer senses the position of the rocket and also updates the position to the ground telemetry system. The ADS/IMU (Air Data Sensor and Inertial Measurement Unit) microcomputer measures the airspeed, attitude and angular velocity using pressure sensors and an inertial sensor. The control microcomputer operates all the actuators onboard. The emergency microcomputer will be activated by the signal from ground, and overwrites actuators command. The data microcomputer logs all the flight data. The system uses RS485 data bus for data transmission.

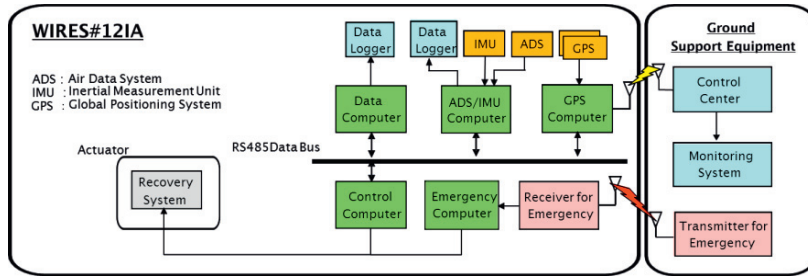


Fig. 5. Block diagram of Avionics and Telemetry

2.3. Recovery system

WIRES#012IA will reach the altitude of 1000 m and during the return flight the deceleration chute is released. The deceleration chute reduces the descent rate of the rocket, to deploy the parafoil. If the descent rate is not reduced, the opening load on the parafoil may damage the rocket structure. Therefore, using the two stage deployment, the load on the parafoil can be reduced. After the deceleration chute deployment, the 3 ring releases, main door is opened and parafoil is ejected. Afterwards, the hanging separation actuator is used, in order to make the rocket into horizontal position following the parafoil ejection. After the hanging separation, the half brakes are released by operating the control line of the parafoil. The three airbags attached to the bottom of the fuselage are also deployed to absorb landing shock. The complete sequences of operations are performed by the on-board control microcomputer within a specific time. The recovery sequences of operations are shown in the Fig. 6

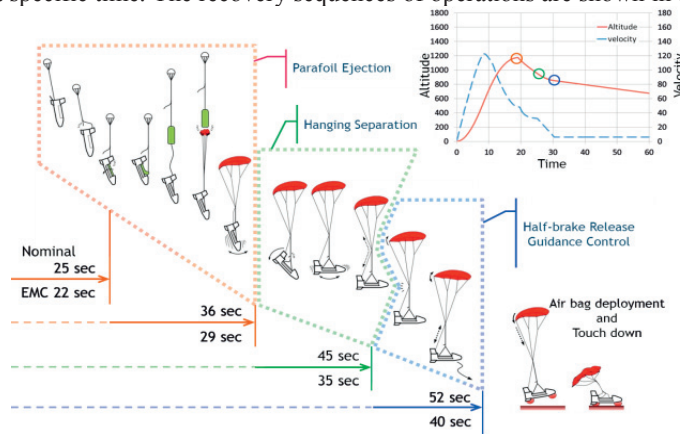


Fig. 6. Recovery Sequence Operations

If there are any abnormalities during the flight such as non-deployment of parafoil at the given altitude, non-reception of telemetry from the rocket or flight outside the safe zone, then the emergency system (EMC) is activated by sending emergency signals from the control center. The emergency system can be activated in two sequences, one is from the actuation of deceleration chute deployment to the guidance control and second is if the control line actuator fails, the secondary actuator (servo motor) actuates and pulls the left emergency control line (Fig. 7) which leads to the swirling of the rocket and makes a safe landing.

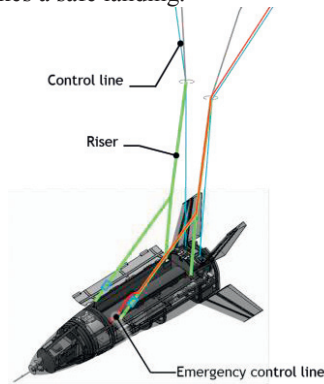


Fig. 7. Control Line and Emergency Control Line for The Parafoil

2.4. Guidance control law

WIRES#012IA performs autonomous guidance and control towards a predetermined target point by controlling the parafoil line and steering the rocket to the required position, based on the position data obtained by GPS. The PD (Proportional and Derivative) controller is used for controlling the parafoil line. The equation of PD controller is shown below in equation (1) and (2).

$$\Delta\dot{\psi}(k) = \frac{1}{T} \{ \Delta\psi_i(k) - \Delta\psi(k-1) \} \quad (1)$$

$$l = K_{\Delta\psi} \Delta\psi(k) + K_{\Delta\dot{\psi}} \Delta\dot{\psi}(k) \quad (2)$$

where l : pulling length of the control line (positive for right line and negative for left line), T : is the sampling time, $\Delta\psi$: is the error angle between target and velocity vectors; $K_{\Delta\psi}$: and $K_{\Delta\dot{\psi}}$: are the proportional and derivative gains, respectively.

First, The GPS data for two instances will be received and the error angle between the target vector and velocity vector is calculated. By substituting this error angle in equation (1) we can determine the angular velocity error. This angular velocity error is substituted in equation (2) to determine the length of the control line to be drawn (Fig. 8). The onboard control circuit performs this calculation and controls the parafoil control line. In this way, the rocket is steered to the predetermined target point.

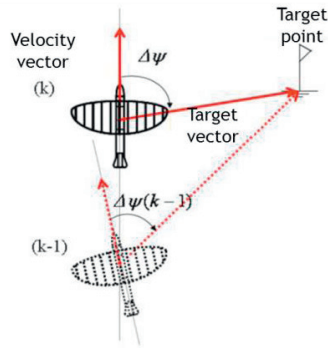


Fig. 8. Description of Guidance and Control law

2.5. Propulsion system

The propulsion system of WIRES#012IA employs commercial hybrid engine HyperTEK M1000 developed by Cesaroni technology Incorporated (CTI). The HyperTEK engine uses Nitrous oxide (N₂O) as oxidizer and Acrylonitrile Butadiene Styrene (ABS) resin as combustion grain. The engine weight is 8.85 kg (with fuel) and produces maximum thrust of 1758 N with a specific impulse of 260 seconds.

3. Combustion test

Two ground combustion tests have been performed on January 9th, 2014 (Fig. 9) and March 5th, 2014 to evaluate onboard thrust profile. The first combustion test was successful. The thrust profile obtained was similar to that of the reference value (catalogue value) but the combustion time was short (Fig. 10). After the combustion, the emergency sequence was also verified. Small design fault with the circuit of the actuator was detected. After the fault diagnosis of the actuator circuit, second combustion test was conducted and the engine achieved the maximum thrust and combustion time was similar to that of the reference value. Also the recovery sequence was successfully verified.



Fig. 9. Combustion Test (January 9th, 2014).

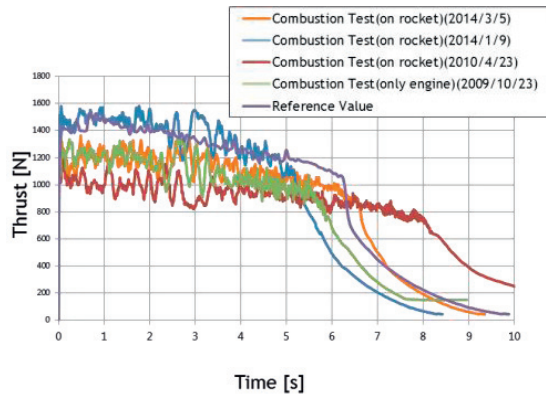


Fig. 10. Combustion Test Results.

4. Flight test

The flight test was conducted on March 11th, 2014. Unfortunately, the flight test was not successful as rocket engine exploded within initial seconds (Fig. 11) of take-off, however the rocket continued the flight and reached the altitude of around 180 m and made a hard landing. The rocket could neither reach the planned altitude because of low thrust nor demonstrate parafoil flight due to low apogee and the damage of equipment.



Fig. 11. Initial Seconds of The Launch

Although the rocket made hard landing, the altitude, attitude, acceleration and angular velocity data were recovered. The data has been compared with the simulation result (considering the 2nd combustion test thrust profile). From the Fig. 12 and Fig. 13, the rocket did not reach the expected altitude and it decelerated sooner than expected due to explosion in the rocket, resulting in unsuccessful demonstration of the guided flight.

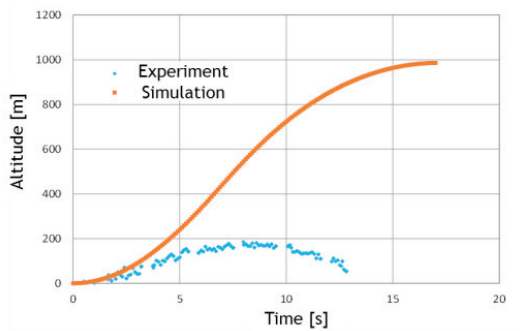


Fig. 12. Altitude Comparison of flight test and simulation

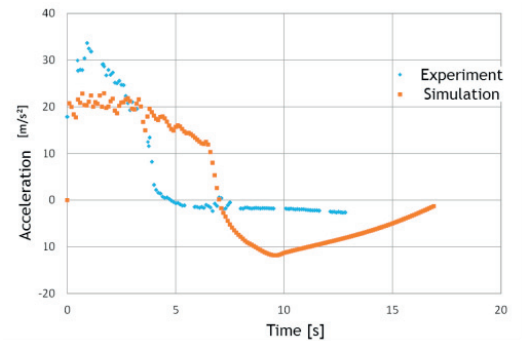


Fig. 13. Acceleration Comparison of flight test and simulation

When the rocket was discovered, the nozzle of the combustor was missing. It was neither found in the vicinity of landing point nor at the launch point. Therefore, authors analysed the videos captured from control centre and it was observed that, 4.6 seconds after take-off the nozzle fell from the rocket. After flight test, authors recovered it (Fig. 14). It was confirmed that the nozzle broke immediately after the ignition, causing a serious damage to the combustor resulting in low-altitude flight due to lack of thrust. After conducting an advanced investigation, various

HyperTEK M1000 grains have been analysed and it was found that grains had some moulding defects. There were many voids found inside the grain, especially near the nozzle after comparing the used and unused grains (Fig. 15).



Fig. 14. Recovered Nozzle

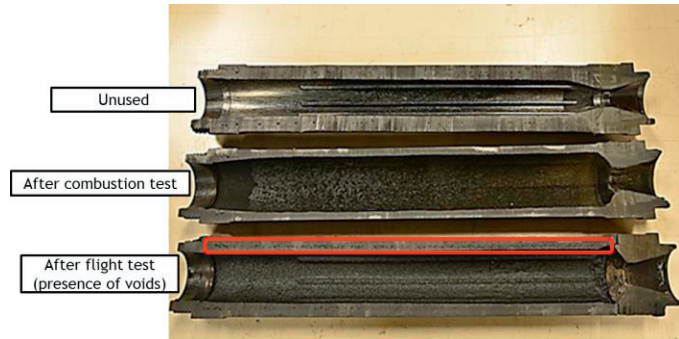


Fig. 15. Presence of Voids in The Grain

5. Conclusion and future works

It was concluded that these grain defects was the cause of explosion resulting in low-altitude flight. Thus, demonstration of autonomous guidance and control of parafoil could not be verified. Currently Kyushu Institute of Technology in cooperation with JAXA, University of Texas, El Paso and other aerospace companies are developing the next version of winged rocket which will be about 4 m in total length and weighs about 500 kg. It is expected to reach the altitude of 6 km, utilises reaction control system for attitude control during the re-entry and advanced guidance, navigation and control system. It will be launched by the end of 2015.

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