Introduction to Resistor-Based Sensors for Feedback Control of Hybrid Rocket Engines

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ABSTRACT

The fuel regression rate in hybrid engines is not directly manageable and depends on the flow conditions in the combustion chamber. However, oxidizer to fuel ratio (O/F) control is required for future applications. In this context, A-SOFT engine studied within the Hybrid Rocket Working Group in Japan was proposed and aims at manipulating simultaneously and independently the thrust and O/F ratio. One of the remaining challenges for such an engine is the instantaneous and inflight fuel regression rate measurement. This paper presents a possible solution for this issue and deals with resistor-based sensors (RBS) currently developed by the Italian university Politecnico di Milano. A recent collaboration between JAXA and PoliMilano was established and the roadmap and current status of the research will be introduced.

Keywords: Hybrid Rocket, Fuel Regression Rate Measurement, Feedback Control

1. INTRODUCTION

By combining a liquid oxidizer and a solid fuel, hybrid propulsion offers several well-known advantages such as high level of safety and theoretical performances, throttling possibilities, environment friendly propellants, etc. However, the combustion occurs in a diffusion flame located in the boundary layer close to the fuel grain surface which tends to limit the combustion efficiency since the propellant mixing is not very efficient naturally. In addition, it makes the O/F ratio control difficult since the regression rate depends on the mass flux in the combustion chamber and varies during operation. The mass flux modification during a firing test is mainly provoked by the fuel port diameter increase: even if the oxidizer mass flow rate is maintained constant, the fuel grain geometry is modified due to the regression. The fuel regression rate is hence modified naturally and so is the O/F ratio. To counteract this natural O/F shift, it is possible to modify continuously the oxidizer mass flow rate and to maintain a target O/F ratio during operation. However, doing so would conduct to modify the thrust of the engine which is not acceptable.

To overcome these limitations, the Altering-intensity Swirling-Oxidizer-Flow-Type (A-SOFT) hybrid rocket concept was proposed and studied by JAXA within the Hybrid Rocket Working Group in Japan. An A-SOFT engine aims at controlling both the O/F ratio and the thrust instantaneously and independently by manipulating the oxidizer injection mass flow rate and the swirl intensity separately. In the case of a swirled oxidizer injection, the regression rate can be empirically described by Eq. 1 [1]:

$$\dot{r} = a_0(1+S^2)^{\alpha}(\rho u)_{ox}^{\beta} \tag{1}$$

The swirl intensity S can be viewed as the ratio between radial and axial momentums and has a strong influence on the fuel regression rate. As a positive consequence, it is theoretically possible to modify the fuel regression rate without changing the total oxidizer mass flow rate and hence to modify the O/F ratio while maintaining a constant thrust level. A swirl injection also tends to increase the combustion efficiency of the engine. The control of the swirl intensity and the total oxidizer mass flow rate is realized by two servo-valves. In practice, to manage both the O/F ratio and the thrust in operation, these quantities must be measured -or properly estimated- in-flight and instantaneously and the measurements need to be integrated into a feedback control loop (Fig. 1). Despite several fuel regression rate measurement's methods exist and have proven their efficiency on ground tests, most of them are not realistic for an in-flight feedback loop control. A potential solution could be to employ resistor-based sensors (RBS) which deliver an electric voltage proportional to their length and which allows to instantaneously follow the fuel grain surface position at different axial locations. A type of RBS was developed by the SPLab from Politecnico di Milano [2] and will be introduced.

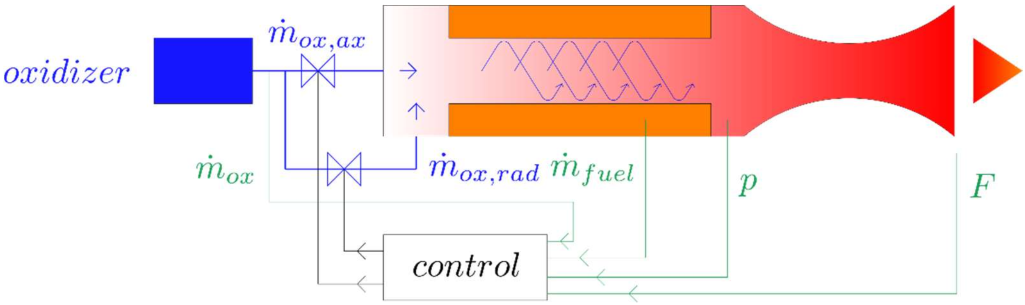


Figure 1. A-SOFT engine concept and its feedback loop control.

2. RESISTOR-BASED SENSORS

2.1. Generalities

The RBS principle is very simple: the sensor is embedded in the fuel grain and regresses with it. While the sensor's length decreases, the electric voltage it delivers changes. It allows to determine the position of the fuel grain surface at the sensor location and to deduce the fuel regression rate. This technology was already developed several years ago such as the MIRRAS sensors [3] (Fig. 2).

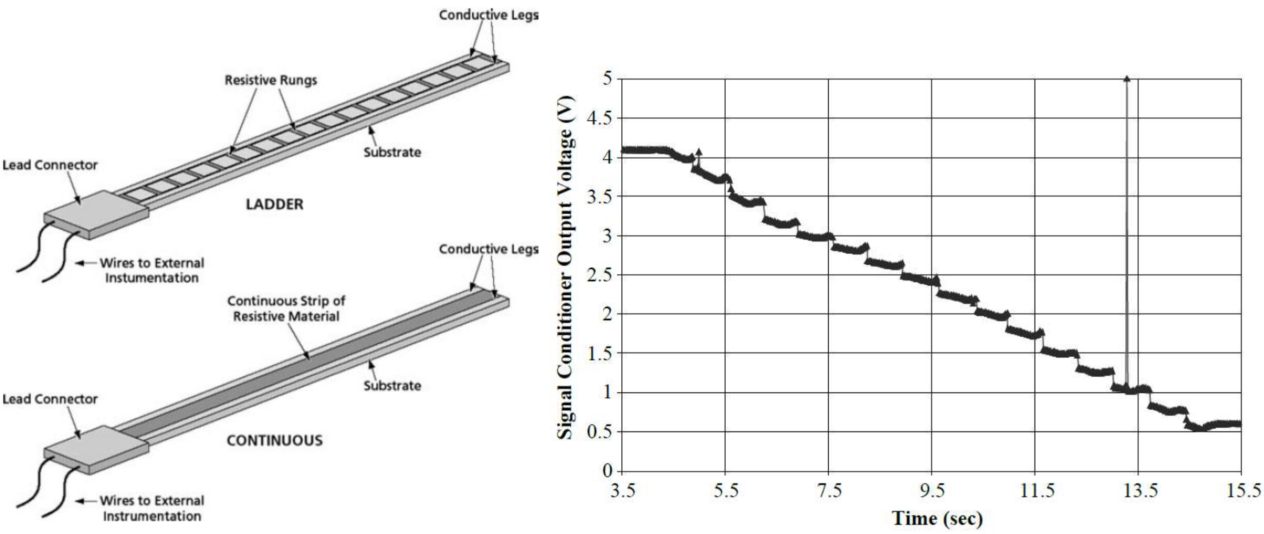
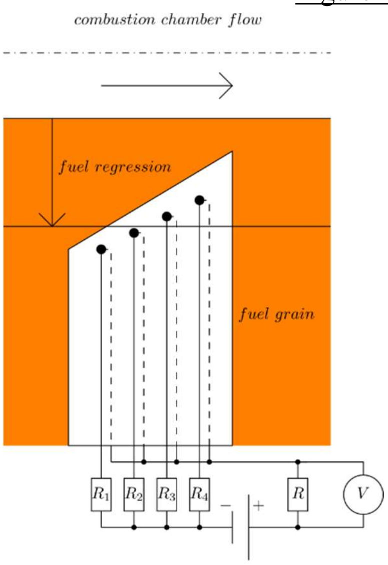


Figure 2. MIRRAS sensors (left) and signal (right).



The RBS developed by Politecnico di Milano are based on the same principle but with a different architecture: the resistors themselves are located outside of the grain. The regression of the sensor's raw material conducts to the disconnection of the resistors and hence to the variation of the output electric voltage (Fig. 3).

Figure 3. Resistor-based sensors principle (Politecnico di Milano).

2.2. Challenges

To predict the theoretical measurements that this type of sensors could provide, a preliminary analysis was performed. Fig. 4 shows the chosen parameters to study the sensors: s_0 is the initial distance between the first resistor and the grain surface, ds and ds_x are respectively the radial and axial distance between two resistors (uniform between all resistors in that case).

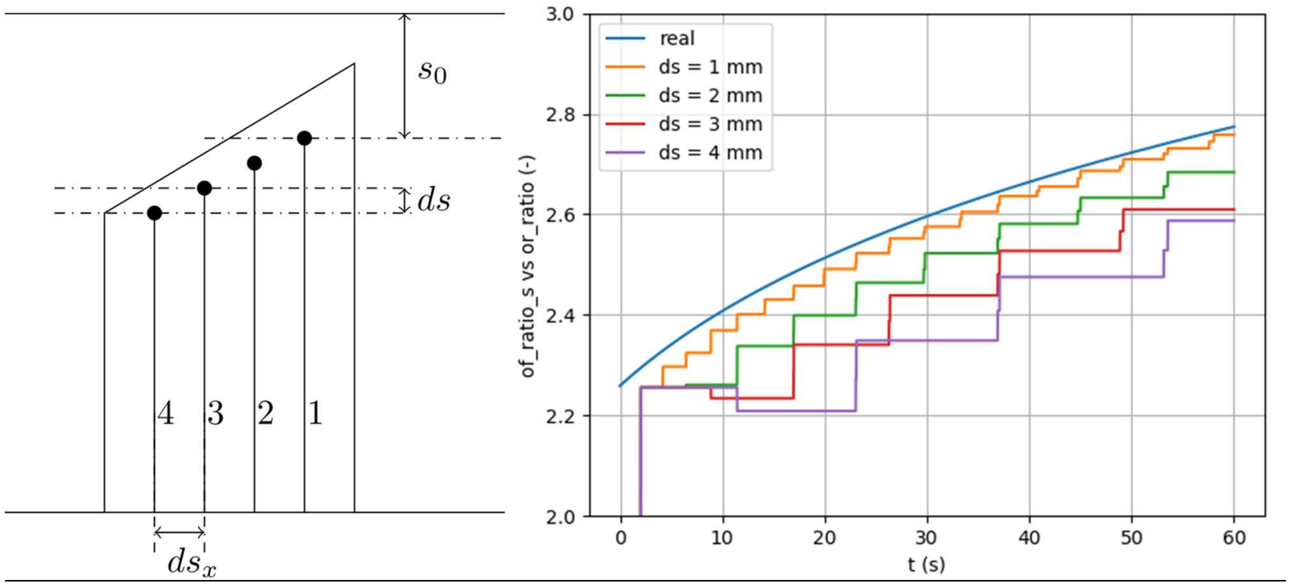


Figure 4. RBS parameters (left) and preliminary analysis results (right).

A one-dimensional numerical code was used to calculate the fuel regression of a hybrid rocket engine based on data obtained from previous firing tests performed in JAXA. The ideal sensor's behavior was implemented in the code so that it is possible to compare the theoretical O/F ratio evolution to the sensor's measurement predictions. Fig. 4 presents the results by changing the *ds* parameter. It can be seen that it has a major influence on the estimation of the O/F ratio and that the smaller this value is the best precision we obtain. We can notice it is required that the fuel surface reaches the first resistor before the evaluation of O/F is possible. Based on this preliminary analysis we could conclude that the ideal sensors would have the lowest *s0*, *ds* and ds_x values. However, it is practically difficult to reach very small values and further studies are required to identify critical values for the desired precision.

3. STATUS OF RESEARCH AND FUTURE PLANS

3.1. Current status

Since these sensors must be embedded in the fuel grain, it is necessary to include them during the manufacturing process of the grain. To do so, it was chosen to employ wax-based fuel and to insert the sensors in the engine case while pouring out the melted wax. Pseudo-vacuum conditions (under 0.1 bar) are established during 45 minutes to remove the bubbles in the liquid wax. The engine case is then pressurized (around 5 bar) and the temperature is slowly reduced thanks to controlled heating ribbons (Fig. 5). This process showed very encouraging results but small cracks are still formed at the surface of the grain, it seems however that the use of additives such as stearic acid or EVA should avoid this issue. When the fuel-grain manufacturing process will be properly managed, firing tests without and then with sensors will be conducted to evaluate the performances of the current version of the sensors. Following this step, new RBS architecture will be developed in collaboration with Politecnico di Milano to satisfy the requirements for future A-SOFT applications.

3.2. Future research

Several aspects should be investigated before making this technology viable for real applications. Since the sensors are embedded in the fuel grain, they may have an intrusive effect on the local regression rate and can possibly have a different burning rate than the fuel since the raw materials are different. The number and location of the sensors in the fuel must be determined to ensure a good precision of the O/F ration measurement. The sensors manufacturing process as well as their robustness must be studied and they also have to be included into a complete feedback loop control coupled with thrust measurements. For future work, it is envisaged to perform firing tests and analysis, and to study new manufacturing processes such as 3D printing. Direct visualization of the resistors regression as well as comparison with other fuel regression rate measurement (for example ultrasonic sensors) are currently being proposed in collaboration with PoliMilano and ONERA.

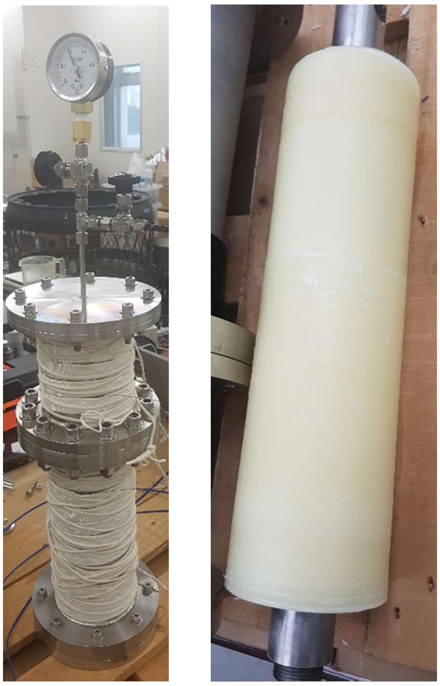


Figure 5. Wax-fuel grain manufacturing process.

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