

# A novel design of MEMS based solid propellant micro propulsion array for micro satellites

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## Abstract:

As the development of small satellites, more commonly referred to as ‘microsats’ with masses in the range of 10-100 kg and ‘nanosats’ featuring masses from 1-10 kg, there emerge several new kinds of space missions, such as the formation flying and constellations of micro satellites, distributed onboard carrier wave radar, high resolution synthetic aperture remote sensing etc. Due to the continuing miniaturization, systematization and complication trend of spacecraft and space missions, onboard propulsion systems are now expected to provide more precision impulse as well as achieving lower volumes and power consumptions. Microelectromechanical systems (MEMS) techniques offer great potential in satisfying the mission requirements for the next generation of micro propulsion systems. Thus since the 1990’s, a number of research organizations, such as NASA, JPL, TRW, ESA, have focused their attention towards the design and fabrication of MEMS based micro propulsions, among which solid propellant micro propulsions are proved to be more applicable for the orbit adjustment and attitude control of small satellites. However, conventional solid propellant micro propulsion systems work without status monitoring and thus lack stability. To overcome the deficiency, this paper presents a novel design of solid propellant MEMS based micro propulsion array that can improve the performance of the previous, details the design scheme, structural simulation, control method and Based on the pressure sensing this propulsion system can automatically make compensation and deliver impulse as precise as possible. In addition, burning efficiency of the propellant can be increased because of the ignition method changed and the gas flow dredging passages added.

## Keywords:

MEMS, Micro Propulsion, Solid Propellant Micro Thruster, Integrated Micro Thruster

## 1. Introduction

During the three advancement of space missions, MEMS technique has played an very important part, especially in the aspects of miniaturization and systematization. At the same time, the space missions have put forward more exacting requirement to MEMS<sup>[1]</sup>. For most of the space craft, propulsion system is one of the key subsystems. But as the development of micro and nano satellites,

conventional propulsion can never meet the precision need of orbit position keeping and attitude control of satellites. And volume and power consumption are another two bottlenecks<sup>[2]</sup>. MEMS techniques offer great potential in satisfying the requirements of the micro propulsion systems of next generation. Therefore, MEMS-based micro propulsion systems have developed rapidly. So far, many MEMS-based micro thrusters were fabricated and tested,

among which solid propellant micro thrusters are proved to be more applicable for the orbit adjustment and attitude control of small satellites because of the tiny impulse bit<sup>[3]</sup>.

Making use of MEMS fabrication and assembly techniques, typical solid propellant micro thrusters often have fuel tank, igniter, nozzle and control circuit integrated in one or two silicon wafer<sup>[4]</sup>. And without moving parts and leaky devices the MEMS-based solid propellant micro thrusters can offer more reliability. Currently, many organizations are doing research on solid propellant micro thrusters, including CNRS in France, QinetiQ Corp. in UK, TRW & JPL in the USA and Tsinghua University in China<sup>[5]</sup>.

However, existing solid propellant micro propulsion systems work without status monitoring and thus lack stability. To overcome the deficiency, this paper presents a novel design of solid propellant MEMS based micro propulsion array that can improve the performance of the previous, details the design scheme, fabrication process, control method and structural simulation. Based on the pressure sensing this propulsion system can automatically make compensation and deliver impulse as precise as possible. In addition the fabrication difficulty has to

some extent been reduced due to the simplified structure.

## 2. Structural Design

The chip of micro propulsion array is made up of two silicon wafer bonded. Each array unit involves an igniter and a burning chamber. The system frame is shown as Fig.1. The main characteristic of this design is that, it originally puts forward a kind of double layer structure of the solid propellant micro propulsion in which the convergent-divergent nozzle is substituted by 4 upside down long tubes and a pressure sensor is integrated in the lower layer.

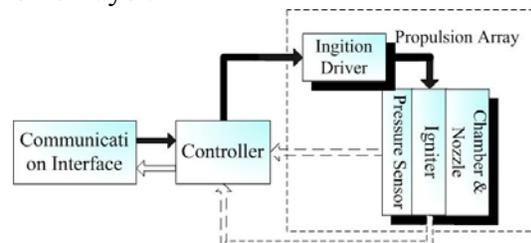


Fig.1. System frame of the integrated micro propulsion array

Fig.2 and Fig.3 show the array structure and the unit structure respectively. As shown in Fig.3, there are four pressure sensing resistances patterned in the form of wheatstone bridge, so that the temperature effect can be counteracted and the sensitivity can be improved.

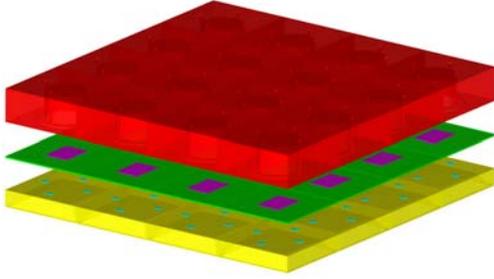


Fig.2. Structure of the micro thruster array

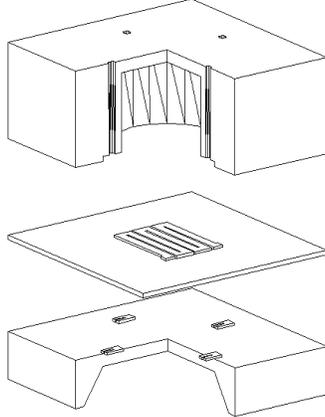


Fig.3. Structure of the micro thruster unit

### 3. Theoretical Model & FEA Simulation

In order to verify the feasibility and evaluate the performance of the novel structure, a theoretical model has been built and analyzed. And a FEA simulation is used to figure out the transient state of the flow and the pressure sensor during the actuation cycle.

#### 3.1 Upper layer

The theoretical model of the upper layer is simplified because the flow field analysis with long tail tubes is complicated. Fig. 4 shows the actual flow vector in the burning chamber and tubes. The entire flow field is divided into two separate part, one is the cylinder chamber

with gas injection and the other is long tail tube whose area of the base plate is the sum of the actual four ones. The simplification results are show in Fig. 5 and Fig. 6.

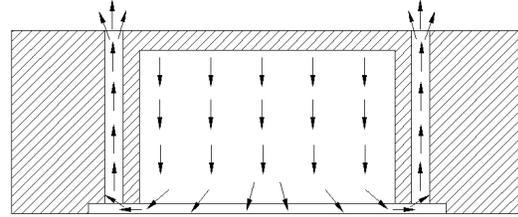


Fig.4. Actual gas flow in the upper layer

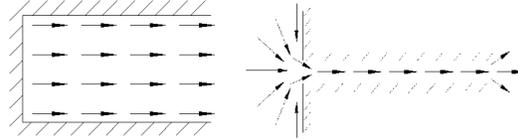


Fig.5. The first part of the simplified structure, cylinder chamber with gas injection.

Fig.6. The second part of the simplified structure, a long tail tube.

First, there comes the flow field analysis in the burning chamber. Through the calculation of this part, the outlet gas velocity is attained. Since the dimension of the burning chamber is far larger than that of the long tail tube, the gas parameters in the burning chamber can be approximately considered to be the same as the stagnation properties<sup>[6]</sup>. Then,

$$T_0 = T_c = 2114K \quad (1)$$

$$P_0 = \left( C^* \times \rho_p \times \frac{S^*}{At} \times a \right)^{1/1-n} = 3.7337 \times 10^5 \text{ Pa} \quad (2)$$

$$r_p = aP_0^n = 6.7429 \times 10^{-3} \text{ m/s} \quad (3)$$

$$\rho_1 = \rho_0 = \frac{P_0}{RT_0} = 0.4418 \text{ kg/m}^3 \quad (4)$$

Where  $T_0$  is the in cavity gas temperature,  $T_c$  is the burning temperature of the propellant,  $P_0$  is the intracavity gas pressure,  $r_p$  is the burning rate of the propellant and  $\rho_0$ ,  $\rho_1$  represent the gas density in the chamber and outlet respectively.

However, the flow velocity in the outlet cannot be taken as equivalent to the stagnation velocity and must be renewedly calculated due to the large velocity gradient there. The estimation of the outlet velocity is based on general gas flow law which can be expressed in the equations below.

$$\rho_p \cdot r_p \cdot S^* = \rho_1 \cdot v_1 \cdot A_t \quad (5)$$

$$v_1 = \frac{\rho_p \cdot r_p \cdot S^*}{\rho_1 \cdot A_t} = 606.63 \text{ m/s} \quad (6)$$

Where  $v_1$  is the outlet gas velocity of the burning chamber or the inlet gas velocity of the long tail tube. According to the inlet gas velocity and the gas flow law in long tube, the in tube gas velocity can be got through Eq. 7<sup>[6]</sup>.

$$\frac{1}{\lambda_1^2} + \ln \lambda_1^2 - \frac{1}{\lambda_2^2} - \ln \lambda_2^2 = \frac{2k}{k+1} f \frac{l}{D} \quad (7)$$

Where  $\lambda_1$  is the inlet velocity coefficient and  $\lambda_2$  is the gas velocity in the position the distance of which to the inlet equals to  $l$ . And  $k$  is the ratio of the specific heat of the gas,  $f$  is the friction coefficient of the tube wall and  $D$  is the

diameter of the tube.

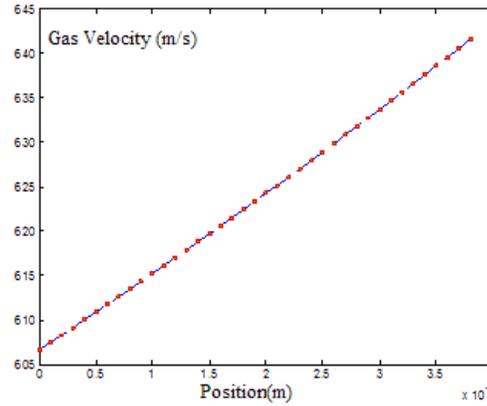


Fig.7 Plot of the gas velocity in the long tail tube

It can be found from Fig.7 that the gas velocity in the tube increases and the outlet velocity is about 641.52m/s. This result may be less than the actual value because the inlet gas density of the tube estimated is a bit larger than the real value. The error can be amended with the FEA simulation results.

The FEA simulation of the flow field is performed in Star-CD, one of the famous CFD softwares. To reduce the amount of calculation and enhance the calculation efficiency. The model in Star-CD is simplified in the similar way stated above. A 7mm outer flow field is built in order to apply pressure boundary. Fig.8 shows the flow model built in Star-CD.

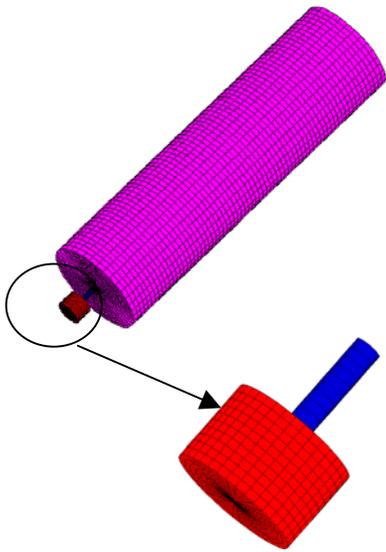


Fig.8. Structure model built in Star-CD

The analysis results, including the gas velocity, pressure and the outlet thrust force are shown from Fig.9 to Fig.11. The highest outlet gas velocity is about  $1012.5\text{ms}^{-1}$  and the maximum thrust force simulated can be up to  $3.6528 \times 10^{-3}\text{N}$ . Using the gas density simulated, the theoretical outlet gas velocity can be corrected to about  $800\text{m/s}$ . As a result, we can arrive at the conclusion that the outlet gas velocity is between  $800\text{-}1000\text{m/s}$ . The values above are almost consistent with the experiment results<sup>[7]</sup>.

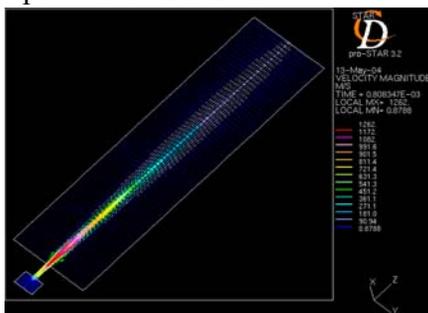


Fig.9. Plot of the simulation result of gas velocity

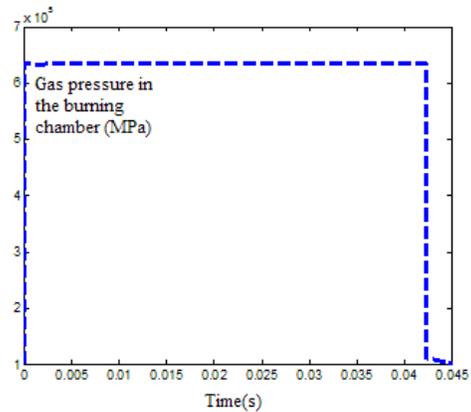


Fig.10. Plot of the simulation result of gas pressure in the burning chamber

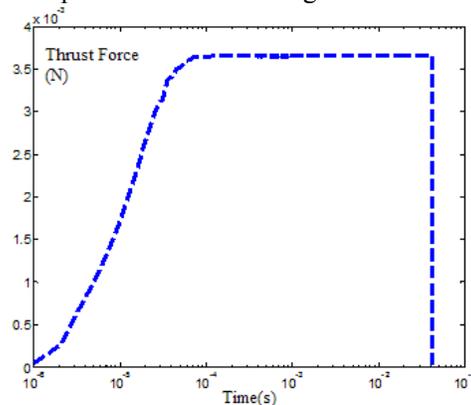


Fig.11. Plot of the simulation result of outlet thrust force

### 3.2 Igniter Layer

The simulation of the igniter layer, which is performed in ANSYS, is primarily focusing on the sensitivity and transient response of the pressure sensor bridge. From the result it can be known that the sensitivity is about  $100\text{mv/MPa}$  and the transient output of the electric bridge varies with the change of the pressure. The variation trend is almost the same as that of the intracavity pressure. Taking into account of the effect of high temperature, the sensitivity is reduced to about  $50\text{mv/MPa}$ .

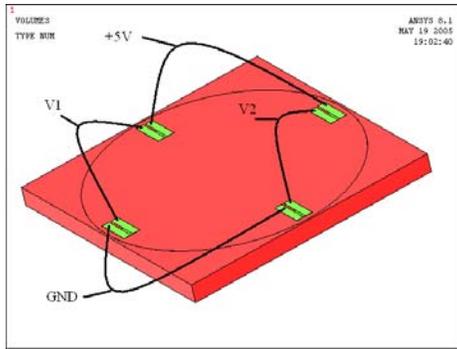


Fig.12. Structure of the igniter layer built in ANSYS

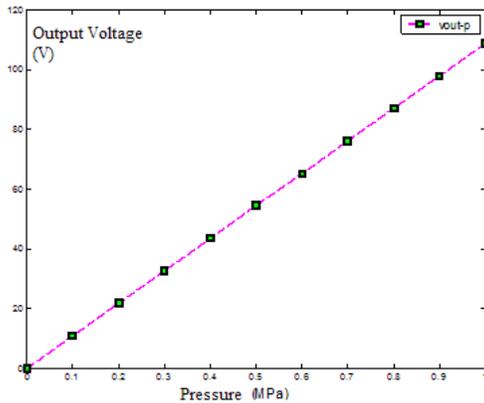


Fig.13. Plot of the output voltage of the electric bridge under different static pressure

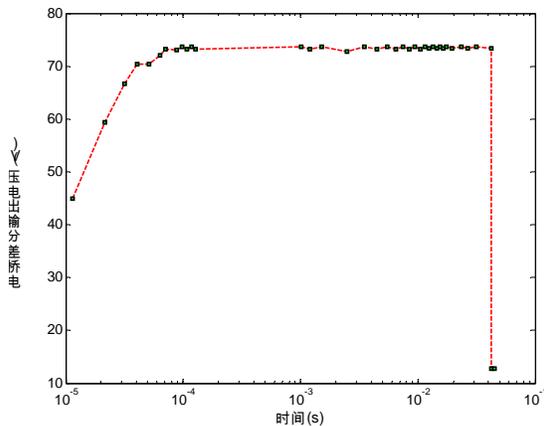


Fig.14. Plot of the output voltage of the electric bridge during the ignition process

#### 4. Control Circuit Design

In the driving circuit we designed CPLD is used as the controller. It takes charge of the work to communicate with uplink module and to drive the propulsion chip to work as the instructions received.

Fig.15 explicitly details the function of the CPLD.

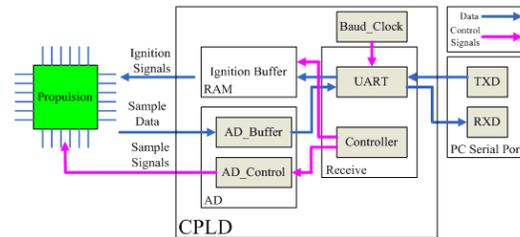


Fig.15. Functional frame of the control circuit

While ignition, the controller can tell the working status of each propulsion unit through the signal the pressure sensors feed back, either in normal station or not totally burnt or even not ignited at all. Then the compensation can be made to achieve the rated value of impulse. It is the auto rectification that makes the propulsion system more precise. Having lower power consumption and space mission experience, RS232 is used as the protocol of communication. The driving circuit board is shown in Fig.16.



Fig.16. Board of the control circuit

#### 5. Conclusion

This paper presents a novel design of solid propellant MEMS based micro

thruster array. The structure is simplified while the functions have been extended. Through theoretical analysis and some experimental testing, this micro thruster array is proved to work normally and can produce a thrust force of several micro newton each unit. And with the extra sensor array layer and appropriate control method, the new micro propulsion array can work as intelligentized as possible.

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