GAS GENERATOR ACTUATOR ARRAYS FOR FLIGHT CONTROL OF SPINNING BODY PROJECTILES

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ABSTRACT

This paper presents batch-fabrication lamination approaches for the realization of large arrays of high-power, short-duration gas generator actuators (GGAs), and system implementation approaches for integration of these GGAs into a 40-mm diameter gun-launched projectile for projectile flight control and course correction. The GGAs are tested to determine the impulse delivered per GGA and the time required delivering the impulse. The arrays of GGAs are connected with control electronics and integrated into a 40-mm diameter projectile. The final result is a flight control system for a small-scale projectile; fabrication and characterization of the actuator component of this system will be presented here.

1. INTRODUCTION

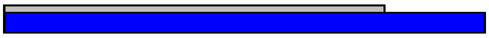
The GGAs are conceptually similar to previous microrockets [1] or micropyros [2, 3] in that solid fuel is combusted within a combustion chamber and exhausted through a nozzle. Solid fuel actuators are useful in applications that require disposable actuators to deliver large specific impulses with simplified fabrication. Unlike previous approaches designed for microsatellite applications, GGAs are designed to operate in atmospheric conditions and can take advantage of flow-control techniques in which the generated gas can interact with the embedding flow surrounding the moving projectile to produce larger-scale forces than those available from the GGA itself [4]. The platform for testing these devices is a gun-launched projectile with a 60 Hz spin rate. Large g-loads, on the order of 10g, are common at launch with gun-fired munitions, so robust materials that are insensitive to shock are laminated to form the GGA arrays. Further complicating the application is the relatively high spin rate of these projectiles, requiring rapid (millisecond-scale) force rise and fall times, rendering many previous approaches inapplicable. This rapid force profile is achieved using appropriately-designed hot-wire igniters that create a larger combustion front, reshaping the force profile of the actuator, thereby generating larger forces in shorter times. Finally, the ignition and control system must be self-contained within the projectile. This requires that the ignition power be matched to the on-board power supply. The devices presented have the following characteristics

- Simplified combustor fabrication
- Robust materials, 10g launch
- Array of single-shot, disposable actuators
- Low voltage ignition, 8 VDC
- Rapid force rise/fall times, less than four millisecond total burn time

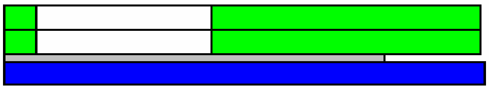
2. FABRICATION

GGA arrays were fabricated using laser micromachining and lamination techniques, **Figure 1**. The materials used to fabricate the GGAs were 250-micron thick Mylar with 10-micron thick pressure sensitive adhesive (PSA) bonded to both sides of the Mylar film, and the igniters were patterned from 15-micron thick Copper-Nickel film. These materials are rapidly patterned using laser machining, and they are robust enough to withstand the high g-load launch. The process for fabricating the combustors is as follows:

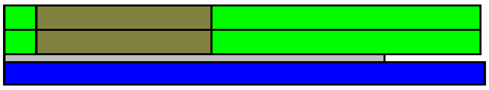
(a) Laser cut Mylar laminae



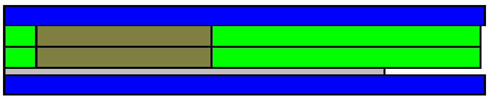
(b) Bond and laser cut igniter layer



(c) Laminate chamber layers to igniter and backing layers

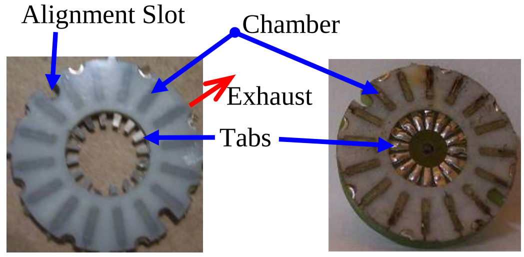


(d) Fill chambers with viscous fuel and allow fuel to cure



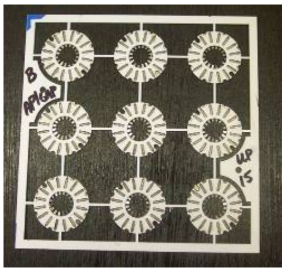
(e) Bond final layer to seal the combustor

Figure 1. GGA Fabrication



(a) GGA Array

(b) GGA Soldered to PCB



(c) 128 x 128 mm panel of GGA arrays Without fuel and final backing layer

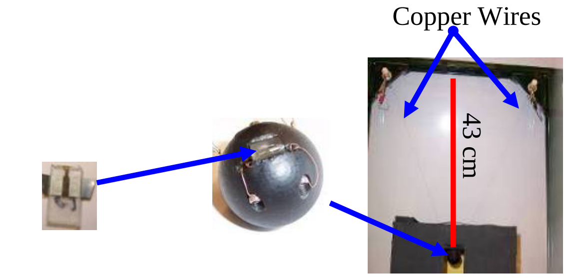
Figure 2. Fabrication Results for 33 mm diameter radial array of Gas Generator Actuators

a) Pattern layers of Mylar using a CO_2 laser to form hollow combustion chambers and solid backing layers.
b) Laminate 15-micron layer of Copper-Nickel film to a patterned layer of Mylar, align assembly to CNC controlled stage, and pattern Copper-Nickel foil with an IR-laser to form an igniter through the combustion chamber. The igniters are 500 x 250 x 15 microns and have a resistance of 1 Ohm. The igniters are patterned with small tabs that make the GGA array a surface mount component.
c) Bond laminae with a hydraulic press at room temperature to form partially sealed combustion chambers. The combustion chambers are 3.3 mm^3, and the nozzle throat is 600 microns x 150 microns. **Figure 2(c)** shows a view of a panel of GGA arrays at the completion of this step.
d) Fill combustion chambers with viscous fuel, and then cure, or harden, the fuel.
e) After the fuel has hardened, bond the final to seal the combustion chamber.

Figure 2 shows two views of the GGA assembly. **2(c)** is a panel of GGA arrays before the chambers have been filled with fuel. When fabrication is complete, individual GGA arrays are released by cutting the interconnecting plastic strips. This yields the GGA array seen in **2(a)**. The array is composed of 16 combustors aligned radially to a 30-mm diameter disk. The volume of each combustor is 3.3 mm^3. The GGA array is aligned to a PCB, and the loose tabs are soldered to contact pads on the PCB as seen in **2(b)**. The top layer in **2(b)** was removed to show the cured fuel in the combustion chamber.

3. COMBUSTOR PERFORMANCE

The GGA arrays are designed to integrate with an axisymmetric, bluff body with a spin rate of 60 Hz. The combustors must deliver an impulse within a 4 ms rotation of the body in order to be delivering force in the desired direction. This action steers the body towards the opposite direction. The ignition delay must be well controlled so the combustor fires in the control direction, making actuator reproducibility an



(a) Single Combustor (b) 19 g Epoxy Pendulum (c) Ballistic Pendulum

Figure 3. Ballistic Pendulum Components

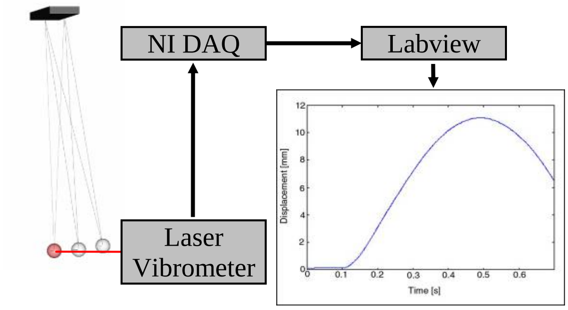
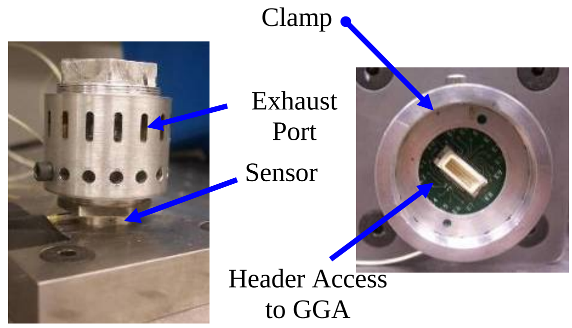


Figure 4. Ballistic Pendulum Setup



(a) Side View (b) Top View

Figure 5. Force Stand Setup

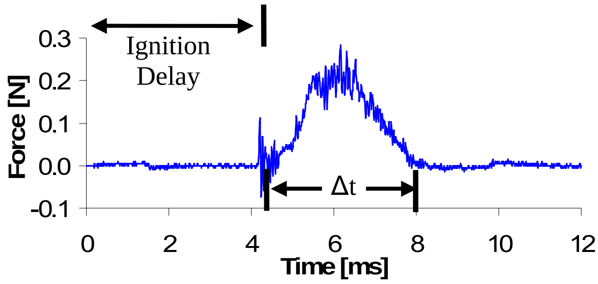


Figure 6. Force Response

important manufacturing constraint. Therefore, the total impulse delivered, the impulse duration, and the ignition delay are characterized in order to control the application of forces to the spinning body. Combustors are characterized using a fixed force balance and a ballistic pendulum. Finally, the GGA arrays are integrated into a windtunnel model and the jet was observed interacting with the flow field.

3.1 Ballistic Pendulum

Total GGA Impulse and Specific Impulse of the propellant are determined using a ballistic pendulum, **Figure 3**. Single combustor chips, **3(a)**, were loaded into an epoxy ball, **3(b)**, and this ball was suspended by two copper wires to create a pendulum arm length of 43 cm, **3(c)**. Electrical power is conducted through the copper wires and then conducted through a mechanical contact to the combustor chip. A laser vibrometer records the position of the ballistic pendulum, and data is digitally recorded. **Figure 4** shows the measurement system and a sample vibrometer output. The initial velocity, initial displacement, and maximum displacement of the ballistic pendulum are used to calculate the total impulse delivered from the combustor. Testing has shown that the 3.3 mm^3 devices filled with polymeric fuel produce impulses of 1 +/- 0.22 N-ms. Combustor mass is measured before and after firing to determine the specific impulse of the fuel that combusted. The mass loss was measured to be 2.2 mg +/- 0.7 mg. The average specific impulse for polymeric fuel mixture tested was 49 s.

3.2 Force Balance

Ignition delay and impulse duration are determined using a stationary force balance, **Figure 5**. A Kistler piezoelectric force sensor is used to record force applied by the GGAs. The GGAs are clamped into the rotating turret, and product gasses escape through machined exhaust ports. Electronic access to each combustor is passed through a central header. The combustor turret is linked to the force sensor through a damped ring to reduce the amount of high-frequency oscillations recorded by the force sensor. **Figure 6** shows a typical force response.

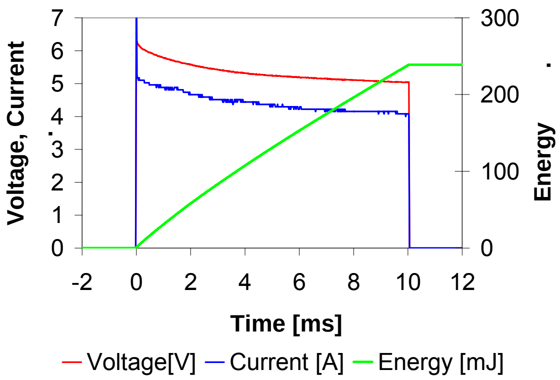


Figure 7. Electrical Input for Ignition

A peak force of 250 mN is recorded 5.8 ms after ignition, and the duration of the force is 3.3 ms. The ignition delay is 4.2 ms when determined to be the start of the combustion event. For the 3.3 mm3 combustor presented, the ignition delay is 4.3 +/- 0.3 ms and the combustion duration is 3.7 +/- 1 ms. Integrating the force curve yields impulses of 0.6 +/- .2 N-ms. These values are smaller than impulse values recorded using the ballistic pendulum because of the damping ring between the combustor turret and the force sensor. The force results show that the combustor impulse can be sufficiently directed as the projectile spins.

3.3 Electrical Operation

The power supply for the GGA arrays consists of two 200mAh Li-ion batteries in parallel with a hybrid-tantalum, 5 mF capacitor. Drive circuitry activates a power mosfet to control the pulse duration to the igniter. **Figure 7** shows the ignition energy delivered to the igniter. The battery voltage with no-load is approximately 8VDC. When the mosfet is activated, 6.2 VDC and 5.2 A is delivered to the igniter. Voltage and current decrease to 5VDC and 4 A as the capacitor discharges and the igniter resistance increases. The total energy delivered is 250 mJ.

3.4 Windtunnel Operation

Finally, system operation is verified by imaging the jet exhaust in a wind tunnel **Figure 8** illustrates successful wind tunnel testing with the GGA exhaust jet penetrating into a 35 m/s crossflow. The jet penetrates into the flow field before being swept downstream. This type of exhaust locally separates the boundary layer from the body, increasing the area of the trailing wake.

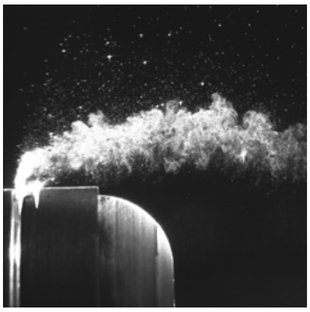


Figure 8. Gas expulsion in cross flow

4. CONCLUSION

The GGA arrays demonstrate a simple fabrication method to produce robust arrays of solid fuel actuators. These actuators are capable of delivering large impulses within millisecond timescales, and the repeatable ignition delay allows for the implementation of these actuators onto a moving, or spinning body. The power supply has been reduced to two batteries, a capacitor, and control electronics which would also facilitate the application of GGA arrays into independent packages. Windtunnel imagery shows significant flow field penetration for a 35 m/s crossflow, suggesting that the combustor forces are on the order of convective flow field forces for this free-stream velocity.

ACKNOWLEDGEMENT

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