JET INTERACTION EFFECT ON THE PRECISION GUIDED MORTAR MUNITION (PGMM)

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ABSTRACT

The XM395 Precision Guided Mortar Munition (PGMM) is a fin-stabilized, laser-guided projectile (Fig. 1) that was being developed for the US Army's 120mm Mortar System. The combination of its precision capability and high-explosive warhead made it very effective against its required target set, personnel protected by masonry walls, bunkers and lightly armored vehicles.

During the PGMM development, numerous projectile firings were conducted. Many of these tests utilized the mid-body thruster mechanism to maneuver the projectile. During these firings a phenomena known as jet interaction (JI) was encountered when thrusters were fired. The JI caused unexpected angular rates to be imparted to the projectiles, resulting in angular motion which decreased the projectile's effectiveness. This report describes the challenges of understanding, characterizing and counteracting the undesirable JI effects.

1. INTRODUCTION

The XM395 PGMM was a multi-purpose 120mm Semi-Active Laser (SAL) guided mortar ammunition capable of maneuvering to its intended target by using advanced Guidance, Navigation, and Control (GNC) processors and a Control Thrust Mechanism (CTM). It was an incremental development program, following the guidelines of evolutionary acquisition. Increment 1 development began in 2004 and was stopped in 2008 due to Army priorities and funding availability.

Fig 1. PGMM being loaded in weapon.

As designed, the PGMM required a man-in-the-loop to designate the target. The PGMM design incorporated a blast fragmenting warhead with a variable delay fuze to provide lethality against the intended target set (troops protected by earth & timber bunkers, masonry walls, or stationary lightly armored vehicles). The following were its key requirements for Increment 1:

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- Cartridge Length: less than 40 inches
- Cartridge Weight: less than 40 lbs
- Maximum Range: 7.2km (Threshold)
- Maximum Range: 10.0km Objective)
- Minimum Range: 500 m

1.1 Projectile Description

The initial PGMM design consisted of three major assemblies (nose, mid-body, and tail) and their associated subassemblies as shown in Figure 2. The final PGMM design is shown in Figure 3.

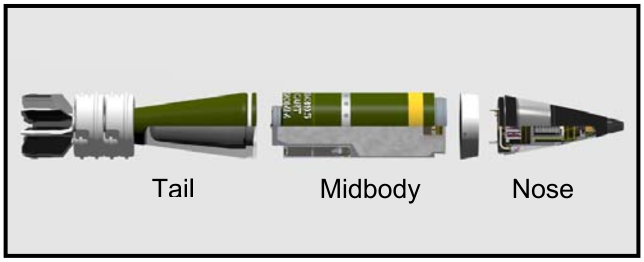

Fig 2. Initial PGMM Increment 1 projectile.

The nose assembly contained the fuze, Integrated Sensor & Electronics Unit (ISEU), and SAL seeker. The fuze contained the battery to power the fuze electronics, the inductive coil for programming mission data into the round, fuze electronics, and the fuze software. The ISEU contained the Guidance & Control Processor, inertial sensors, GN&C flight software, and thermal battery to provide power. The SAL seeker contained the optical window, the collecting optics, relay optics, SAL electronics, and SAL software.

The tail assembly was comprised of an integral boattail/boom, obturator, fin assembly, M1020 ignition cartridge, and four equal propellant charges. As shown, the original design had fixed tail fins, similar to conventional mortar cartridges. The tails fins were canted to provide spin to the projectile.

The mid-body assembly contained the warhead, the Warhead Initiation Module (WIM), and the CTM. The original CTM design had 15 nozzles for a two chamber (each) thruster rocket cavity (rockets laid end to end). After the first rocket was fired, it cleared the cavity to allow the second nozzle to fire (when commanded). This design was later changed to 30 individual thruster chambers with one thruster motor each. The warhead design was a steel case filled with 8.2 lbs of PAX-28 explosive to provide a lethal blast/fragmenting mechanism. The WIM housed the detonator electronics, the Safe & Arm (S&A), and the booster. The CTM contained the thruster igniter assembly and the thrusters.

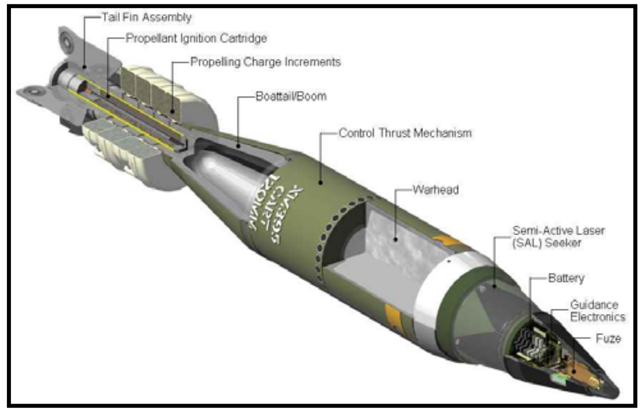

Figure 3. Final PGMM design at conclusion of program.

1.2 Projectile Control

The PGMM utilized a ballistic trajectory to deliver the projectile to an acquisition basket for the SAL to acquire the laser designated target. After target acquisition the CTM was enabled and maneuvering could begin. The inertial sensors were used to determine down and aid in determining the angle to the designated target. Control thrusters provided PGMM with its control authority. The thrusters could be fired individually or in sequence as the projectile rotated them into position. A thrust manager decided which thrusters were to be fired during a given maneuver, keeping track of which thrusters were still available.

1.3 PGMM Flight Test Program

Initial flight tests of the PGMM projectile were performed using inert ballistic flight units which did not have warheads or CTM units. During these tests the projectiles exhibited stable flight over a wide range of zones and quadrant elevations.

Maneuver flight test projectiles were equipped with live CTM units that were preprogrammed to fire groups of divert thrusters at specific times in the trajectories. The maneuver rounds were not intended to steer to a target. Instead, a predetermined number of thrusters were fired in a specific direction (i.e. five thrusters to the right). The maneuver projectiles also contained an integrated telemetry module (ITM), which among other things contained sensors (including magnetometers, sun sensors, accelerometers and rate sensors) to measure the motion of the projectile throughout its' flight and also transmitted the sensor measurements during the flight (Davis, et al, 2007). The ITM units were stored in the warhead cavity and had diagnostic functions for in-flight measurements similar to those of other Army Research Laboratory telemetry systems (Davis, et al., 2004).

Guided flight tests were performed with projectiles that were fully tactical, except for the warhead. They used on-board guidance and control to autonomously steer towards laser designated targets. Once again, the warhead cavities were used to store the ITM units.

2. JET INTERACTION PHENOMENA

2.1 Jet Interaction Discovery

It was during the maneuver tests that the JI effect became apparent; the projectiles experienced large angular rates when the divert thrusters were fired. This was not expected since the thruster nozzles were placed very close (within 1mm) to the projectile center of gravity. Figure 4 is a plot of the total angular rate (root sum square of the pitch rate and yaw rate) measured prior to, during and after a divert event. The large angular rates imparted to the projectiles were attributed to JI, which is a phenomena that occurs when a jet (such as the divert thruster) is exhausted into a crossflow, disrupting the uniform flowfield about the body. While the duration of each thruster burn is relatively short (approx. 20ms) the transient pressures acting on the body can result in significant forces and moments. The large exhaust plume that is present during thruster operation is evident in Figure 5, which is a photograph of an in-flight PGMM projectile taken while the thruster is firing.

Figure 5. PGMM during divert event

2.2 Historical Perspective

A subsequent literature search found that jet interaction is a well known problem and has been studied for many years. Most JI research focused on supersonic/hypersonic flight regimes because reaction jets were used extensively in steering missiles and reentry vehicles. Several sources were found that discusses the JI effect of a supersonic jet into a subsonic crossflow about a body of revolution (Cassel, et al., 1969; Gilman, 1971; Margason, 1993; Cassel, 2003; Beresh, et al., 2005; Spaid and Cassel, 1973). One reference (Margason, 1993) was particularly useful due to its extensive bibliography of 333 documents relevant to the JI phenomena.

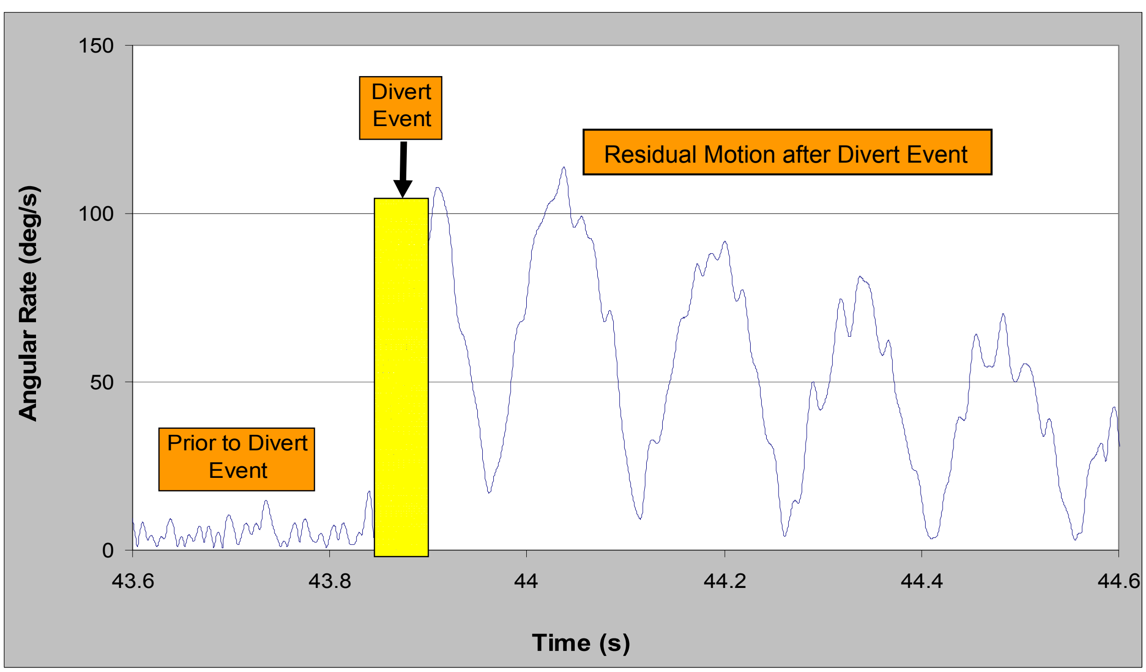

Figure 4. Angular rates measure before, during and after a divert event.

From the literature, it is quite clear that a small high pressure region forms upstream of the exhausting jet and a larger low pressure region forms behind the jet (Cassel, et al., 1969). The latter region encompasses the entire aft end of the projectile including the fins (Beresh, et al., 2005). In addition, the jet-crossflow interaction causes the formation of a vortex system that affects the downstream flowfield (Fig. 6). The vortex is induced as the jet is turned over and realigned by its encounter with the freestream (Beresh, et al. 2005). The far wake of the interaction includes a vortex field which can have significant effects when lifting surfaces are located downstream of jet controls (Spaid and Cassel, 1973). The effect of JI on a flight body is so significant, that activation of the reaction control produces forces and moments on the vehicle that are similar to those resulting from the deployment or deflection of a control surface (Cassel, 2003).

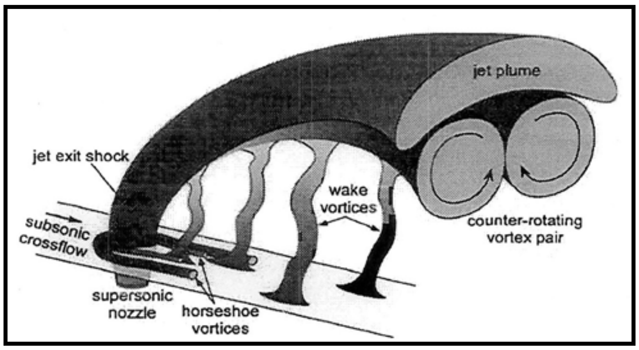

Figure 6. Vortex system induced by jet interacting with crossflow.

2.3 JI moment measured on the PGMM

Using the on-board acceleration and angular rate measurements during (and after) the maneuver events, it is possible to characterize the JI effect. Of particular interest was the angular rate imparted to the projectile since this initiates an angle of attack motion that the guidance and control system must account for to effectively steer to the target. To obtain the JI moment, an equation was derived to calculate the JI moment using known quantities for the projectile and thruster event. It assumes conservation of angular momentum and that the angular rate measured by the on-board rate sensors is due to two moments: one created by the thrust force (from nozzles not being located exactly at the CG) and the JI moment. These calculated JI moments were also independently verified by using a six degree-of-freedom trajectory simulation, checking that the residual angular motion matches that measured by the magnetometers and solar sensors.

A large database of JI moments was obtained by analyzing the flight data of more than 100 maneuver events from 25 PGMM flight tests. The JI moment was found to be strongly dependent on flight Mach number. The JI moments for all events are plotted versus Mach number in Figure 7. There is very little scatter in the JI moments at low Mach numbers, but the scatter increases as the Mach number increases. This scatter is believed to be due to angle of attack dependence and is more evident at higher Mach numbers where the increased dynamic pressure places larger forces and moments on the body. While there are indications that angle of attack has a significant affect in supersonic flight (Brandeis and Gill, 1998), no references were found that discuss this in the subsonic flight regime.

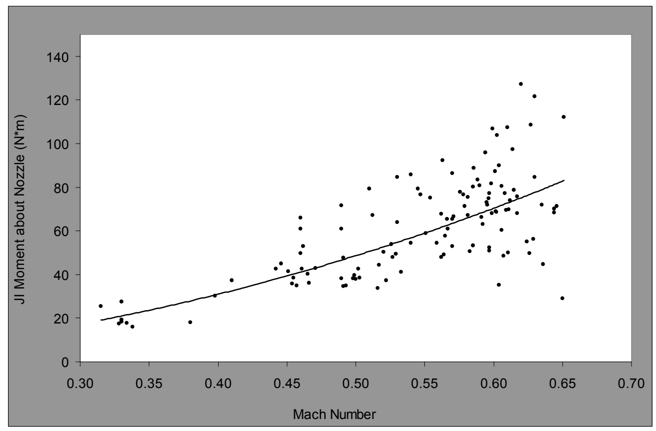

Figure 7. JI moment as a function of Mach number.

In an effort to better understand what parameters were causing the scatter in the JI moment, a statistical study was undertaken. This study found that the JI moment was also strongly dependent on dynamic pressure. It also found weak correlation with total impulse.

2.4 JI force measured on the PGMM

The exhausting jet also causes a lateral force to be imparted (besides that of the thruster itself) to the projectile (Cassel, et al., 1969; Gilman, 1971; Margason, 1993; Cassel, 2003; Beresh, et al., 2005; Brandeis and Gill, 1998). The ratio of the force measured in free flight to that measured in a static test is known as the thrust force amplification factor, K. During the PGMM flight tests, the lateral forces imparted to the projectiles (the measured accelerations were used to calculate the forces) did not match the thrust forces measured during static bench tests. The average impulse measured in-flight (average of 455 thruster firings) was 5.94 lbf-s, whereas the impulse measured on the static test stand was 7.0 lbf-s, resulting in K = 0.85. This is consistent with the results obtained during a wind tunnel investigation where control jets were exhausted from a tactical missile configuration (Gilman, 1971).

For supersonic projectiles K is typically well over unity and it and can be optimized by changing the axial location of the thruster on the body. Designers try to maximize the K as a means of increasing the control authority of the thrusters (Cassel, 2003; Brandeis and Gill, 1998). In general, increasing K is accomplished by placing the nozzles very close to the aft end of the projectile. This would not be a viable option for the latest PGMM projectile design.

2.5 CFD Analysis

To better understand the JI phenomena, a series of computational fluid dynamic (CFD) studies were performed (DeSpirito, 2006; Lewis, 2006) on the PGMM projectile with the divert thruster exhausting into the free stream air. The CFD results clearly show the extent to which the flowfield about the projectile is affected by the thruster exhaust. Figure 8 shows the theoretical pressure field about the PGMM projectile flying at Mach 0.50, during thruster operation. The high pressure region upstream of the exhaust jet and the large low pressure region aft of the jet are evident in this figure. Note the fixed fins modeled in this analysis are those of the initial PGMM increment 1 design; the folding (supercaliber) fins, as seen in Figures 3 and 5, were implemented later in the program. The body surface pressures, as predicted by the CFD, are shown in Figure 9. The CFD results did predict the JI moments during thruster operation, however, the magnitudes were smaller than those measured in free flight. The CFD analyses also showed:

- The force amplification was predicted to be 0.87, nearly identical to that obtained from free flight testing.
- The JI moment varies with nozzle location.
- There is a correlation between the JI moment and the projectile angle of attack.
- The properties of the exhaust gas have an influence on the resultant flowfield, which agrees with historical data.

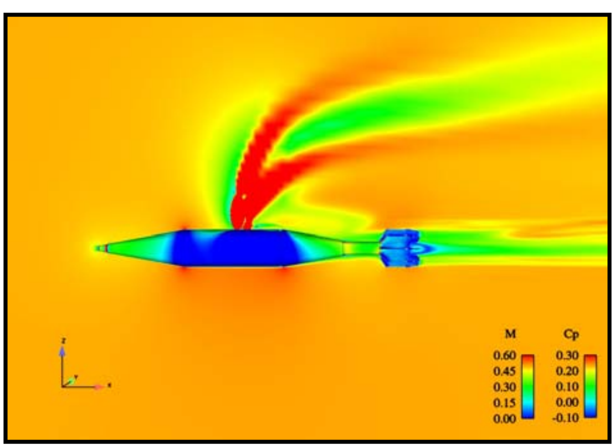

Figure 8. CFD prediction of flowfield during thruster operation.

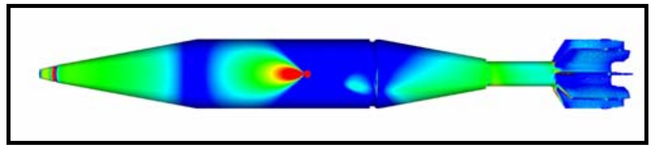

Figure 9. CFD surface pressure predictions**.**

3. COUNTERACTING JET INTERACTION

Once the JI was identified, several changes were made to the projectile system to minimize the adverse effects on the overall system performance.

3.1 Increased static stability

The initial PGMM design (Fig. 2) had fixed fins that were the same diameter as the body. The folding, super-caliber fins (seen in Fig. 5), which significantly improved static stability, were added to decrease the magnitude and duration of post-maneuver angular motion. The increased static margin reduced the adverse JI effects and improved the overall system performance.

3.2 Nozzle location

To help counter the undesirable JI moment, the thruster nozzles were relocated aft of the projectile CG. The moment created by the offset thruster helped balance the JI moment and resulted in improved performance. However, since the JI moment is Mach number (or dynamic pressure) dependent, there is no single nozzle location that will cancel the JI moment at all flight conditions. For the current program the nozzles were placed at a location that reduced JI effects for most flight conditions and statistically maximized the overall system effectiveness.

3.3 Jet interaction model

Based on the data shown in Fig. 7, a JI model was developed and programmed into the projectile's on-board guidance and control system. Estimates of the projectile velocity and atmospheric temperature at the time of the event were required. Incorporating this model allowed the projectile to anticipate what angular rate would be imparted to the projectile as a result of a commanded thruster event. This decreased the time required for the Kalman Filter to determine the projectile's attitude and thus improved the overall system effectiveness. A similar model could be developed using the dynamic pressure, which would require estimates of projectile velocity and local air density.

3.4 Test results

After implementing the improvements discussed above, the PGMM projectile was successfully demonstrated with high reliability during several test series. The projectile repeatedly detected the target, maneuvered, and impacted on target, when fired at various velocities and quadrant elevations. Understanding and countering (where possible) the JI effect played a vital role in the success of the PGMM program.

3.5 Future improvements

Based on the lessons learned from the PGMM program and from information found in the literature, there are several modifications that may further decrease the adverse JI effects on the PGMM projectile in subsonic flight, including:

- Change the nozzle shape (rectangular slot);
- Decrease the thruster burn time.
- Move nozzles further rearward (would required shortened propellant grains);
- Allow thrust manager to use measured angular rates to determine real-time JI effects on projectile;
- Move the projectile center of gravity (forward) relative to the nozzles.
- Develop and incorporate a JI model that is a function of dynamic pressure.

CONCLUSIONS

The PGMM projectile development program encountered a challenging problem when JI adversely affected the projectile dynamics during maneuver events. If ignored, this would have ultimately led to poor system effectiveness. However, steps were taken to understand and then reduce the JI effect, enabling the PGMM program to successfully demonstrate repeatable target impacts under a variety of launch conditions.

The following are the JI lessons learned on the PGMM program:

- The JI moment will impart angular rates to projectile;
- The lateral force exerted on a body in free flight is not same as that measured on static test stand., which will effect maneuverability;
- The JI moment is a strong function of Mach number (and dynamic pressure);
- The JI moment is a function of angle of attack and the effects are most evident at high Mach numbers;
- CFD is a powerful tool and its use played a critical role in understanding how JI influences the flow about the projectile and assisted in understanding the JI phenomena

The key lesson learned by the program office was to get the system into its realistic environment as soon as possible in development, and ensure that a high quality and reliable telemetry system is on board in order to record what is really happening in flight.

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