

TRAJECTORY CORRECTION USING IMPULSE THRUSTERS FOR CONVENTIONAL ARTILLERY PROJECTILES

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Six degree-of-freedom simulations were performed on a 105 mm C132 artillery projectile using the CONTRAJ module of PRODAS. The objective of this study was to determine the impulse thrusters' configurations that yield the best control authority and thus the greatest amount of correction on the projectile trajectory. It was also desired to explain the underlying physical reasons for the varying performance of the impulse thrusters. Contrary to finned projectiles, spin stabilized projectiles exhibit a gyroscopic response 90 degrees out-of-phase with the direction of the perturbation force. This renders the prediction of the thruster's impact on the projectile's trajectory much more difficult. Results indicated that locating the impulse thruster at or aft of the center of gravity provides greater drift correction for a given impulse magnitude. Reasons for this behaviour are explained. It is also shown that impulse thrusters with a burning intensity between 15 and 20 Ns would provide adequate course correction for a 105 mm artillery projectile. The use of several impulse thrusters along the trajectory of the projectile was investigated and shown to increase significantly the amount of correction achieved in drift.

INTRODUCTION

A collaborative project between the French-German Research Institute of Saint-Louis (ISL) and Defence R&D Canada has for objective the development of a better understanding of the use of impulsers on artillery projectiles and their impact on the aerodynamics of these ammunitions. The impulse thrusters consist essentially in small detonators generating a high force for a very short period of time. The impulse thrusters differ significantly from the more conventional jet thrusters in that the impulse is created by the detonation of explosive material as opposed to a gas accelerated through a nozzle. The impulsers will be developed and manufactured at ISL. The thrusters will

be mounted inside the projectile at a specific axial location in a ring-like fashion. They will be used to divert the projectile laterally.

Research and development on the use of thrusters or reaction jets in order to improve the precision of fin stabilized projectiles such as missiles and rockets has been going on for decades now. Over the years, a significant amount of research was performed in order to understand the interaction of the reaction jets with the projectile's external flow as demonstrated by Champigny and Lacau [1] review paper. Furthermore, several investigators studied the loads caused by lateral pulse jets on projectile body. Brandeis and Gill [2] performed an experimental study on the effect of a lateral jet on the forces and moments on a supersonic missile. Recently, trajectory corrections using impulsers have been investigated at ISL for a project on a guided supersonic finned projectile [3].

For spin stabilized projectiles, the use of impulsers or jet thrusters is not as frequent and the technology is still very much into the development phase. Horwath and Barnych [4] presented a concept of a Low Cost Course Correction (LCCC) technique applied to a 40 mm projectile and making use of impulsers. Magnotti et al. [5] tested similar LCCC fuzes on an experimental mortar projectile. Flight path corrections of up to 6.0 mils were obtained using an impulse of 2.6 Ns.

Research on the impact of thrusters or impulsers on the flight dynamics of spinning projectiles is very scarce in the open literature. Using the projectile linear theory, Cooper [6] has shown analytically that the effect of an impulse on a spinning projectile was to produce an additive contribution to the usual aerodynamic jump of the free-flight projectile with no applied impulse. Burchett et al. [7] developed closed-form expressions for the swerving motion of a dual-spin projectile in atmospheric flight under the action of lateral pulse jets.

Research and development is currently ongoing in order to increase the magnitude of the impulse generated by thrusters and also to reduce the size of these devices. An example of such work is that of English et al. [8] who developed a high-power, short-duration MEMS-sized gas generator actuator for spinning projectiles.

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NUMERICAL PROCEDURE AND PROJECTILE CONFIGURATION

PRODAS and CONTRAJ Module

This work was performed using PRODAS (PROjectile Design/Analysis System). PRODAS provides an effective semi-empirical tool that allows for the rapid and complete design of projectiles. The projectile used for the simulation was modeled using PRODAS model editor. The aerodynamic coefficients used for the trajectory simulations are those predicted by the Spinner2004 module of PRODAS. The aerodynamic predictions of PRODAS are based in part on prior experimental testing through the use of a projectile database. In order to improve the reliability of the aerodynamic model, form factors were used to match the drag coefficients to that obtained from radar traces. Additional adjustments to the aerodynamic coefficients were made in order to match the official firing table for the reference projectile used.

The trajectory simulations were performed using the CONTRAJ module of PRODAS. This is a six Degree-Of-Freedom (6DOF) control flight simulation program developed to simulate flight performance, evaluate trade-offs, and provide estimates of operational capability and limitation for projectile equipped with thrust or impulse control. The impulse thrusters' parameters include the start time, the duration, the thrust, the axial location, the tilt and roll angles.

Projectile Configuration

The baseline projectile configuration used for this project is shown in Figure 1. It consists of a 105 mm HEER (High Explosive Extended Range) C132 artillery projectile. This projectile features a base bleed. However, for the needs of this study, it was not simulated. The nominal projectile weight is 12.7 kg and its length 566 mm. The muzzle velocity of the projectile was taken to be 718 m/s, which is essentially that obtained when launched from the LG1 MK2 Howitzer. The spin rate of the projectile was set at 2387 rad/s.

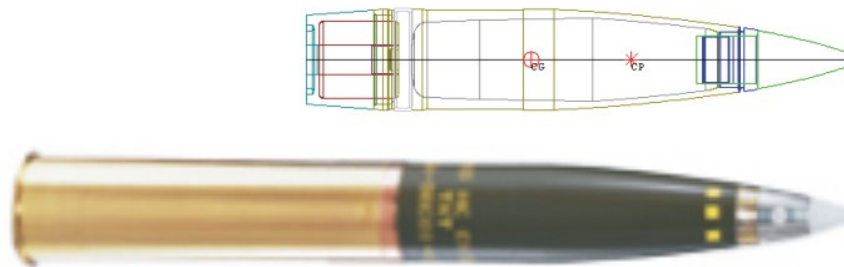


Figure 1. Picture of the 105 mm C132 artillery projectile together with the PRODAS model used for the simulations.

RESULTS AND DISCUSSION

As mentioned previously, one of the main goals of this study was to establish the optimum configuration for impulsers mounted on an artillery projectile. As a first phase, the capacity of a single impulser to alter the trajectory of the projectile in drift was investigated. This was achieved by varying the axial location of the impulser along the projectile body on both the port and starboard sides. Impulses of 20 Ns and 30 Ns were used for these simulations. The impulse thrusters were triggered past the apogee on the downward part of the ballistic trajectory at a flight time of 41 seconds out of a total flight time of 68.7 seconds. The results of that study are presented in Figures 2 and 3. Initially, simulations were performed with an impulser thruster located on the port side of the projectile (left side when looking from behind), thus contributing to an increase in the projectile's drift. The results are presented in Figures 2 and 3, and correspond to the filled symbols. From these figures, it can clearly be seen that the efficiency of the impulser at correcting the trajectory increases significantly when positioned further aft on the projectile body. In fact, positioning the impulse thruster at the center of gravity yields very acceptable performance with the advantage that it does not induce any perturbation to the yaw angle cycle as shown in Figure 4. This, in turn, eliminates the perturbation to the pitch angle cycle brought about by the gyroscopic response (Figure 5). However, it is a surprising result that essentially no drift correction is obtained when the thruster is located close to 2 calibers forward of the center of gravity whereas significant correction is obtained when it is 2 calibers aft of the center of gravity. This is explained by the fact that when the thruster is located forward of the center of gravity, the yaw cycle oscillation following the impulse is in a direction opposite to the desired correction direction as shown in Figure 4 for a flight time between 41 and 43 seconds. The initial yaw cycle oscillations are in the same direction

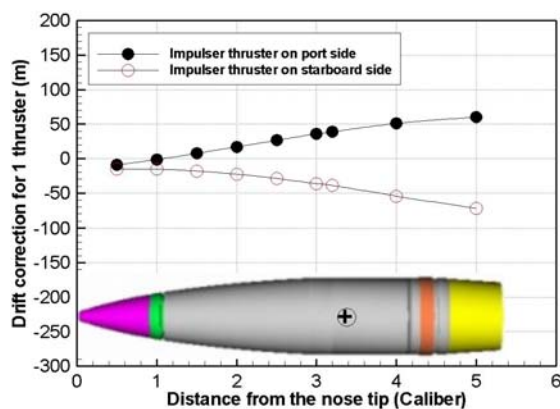


Figure 2. Drift correction as a function of nose tip distance for a 20 Ns impulse thruster triggered at a flight time of 41 s.

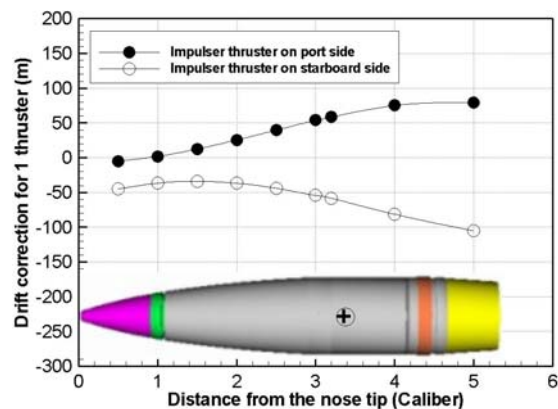


Figure 3. Drift correction as a function of nose tip distance for a 30 Ns impulse thruster triggered at a flight time of 41 s.

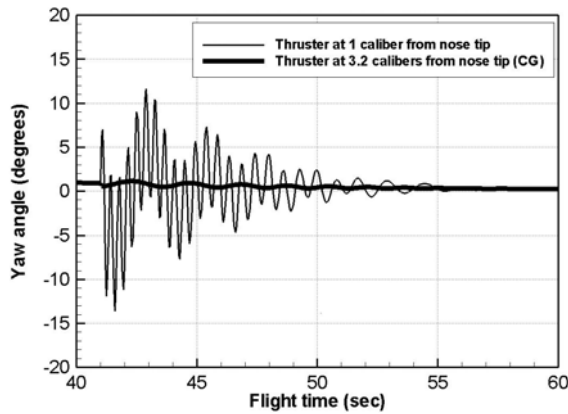


Figure 4. Yaw angle variation with flight time following the ignition of a 20 Ns impulse thruster located on the port side of the projectile.

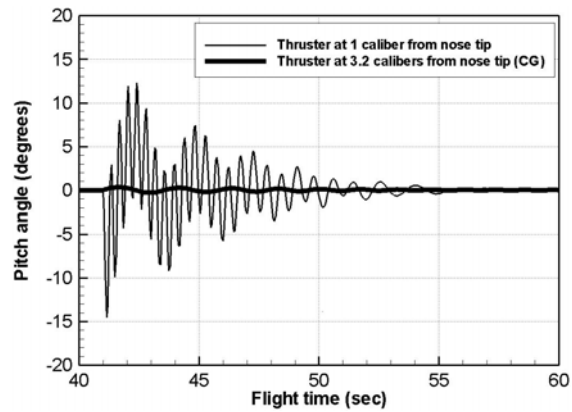


Figure 5. Pitch angle variation with flight time following the ignition of a 20 Ns impulse thruster located on the port side of the projectile.

as the impulse when it is located aft of the center of gravity. This can be seen from Figure 6.

Another important aspect that can be observed by comparing Figures 2 and 3 is the effect of the impulse magnitude on the trajectory correction achieved. Figure 2 shows the correction achieved in drift for a 20 Ns impulser whereas Figure 3 shows that achieved by a 30 Ns impulser. As expected, a smaller impulse results in smaller drift corrections. On the other hand, the trends observed in the variation of the drift correction with axial position of the thruster are very similar for the two impulse magnitudes investigated as seen in Figures 2 and 3. The reduced drift correction obtained when using 20 Ns impulsers does not preclude the use of these as the drift correction achieved with the 20 Ns impulsers is still significant in relation to the precision performance of the 105 mm round. The 105 mm HEER C132 artillery projectile has a Probable Error in Deflection (PED) of less than 2 mils when fired at high angles [9]. This translates into a PED of 20 m for a typical range of 10000 m. Referring back to Figure 2, for a single 20 Ns impulser located behind the center of gravity at 4 calibers from the nose tip, a drift correction of about 50 m can be obtained in either directions. In theory, this is sufficient to bring 91% of the round on target in the azimuthal direction.

The main advantage of using smaller impulsers resides with the significant reduction in yaw and pitch oscillations obtained following the detonation when it is not located at the center of gravity. This can clearly be seen by comparing Figure 4, which shows the yawing motion for a 20 Ns impulser, with Figure 7 which presents the corresponding results for a 30 Ns impulsers. Locating the impulser closer to the center of gravity (3.2 calibers from the nose tip) further reduces the yaw motion as seen in Figure 6. The smaller impulser induced yaw and pitch angles result, in turn, into lower drag and a

reduction in the loss of range. As an example, for a 30 Ns impulser located at 1 caliber from the nose tip, the reduction in range was 240 m whereas a reduction of only 25 m was determined for the same impulser located at 4 calibers from the nose tip. Lower impulses also limit the risk of destabilizing the projectile. Based on the previous discussions, the ideal axial location for the impulse thrusters appears to be either at

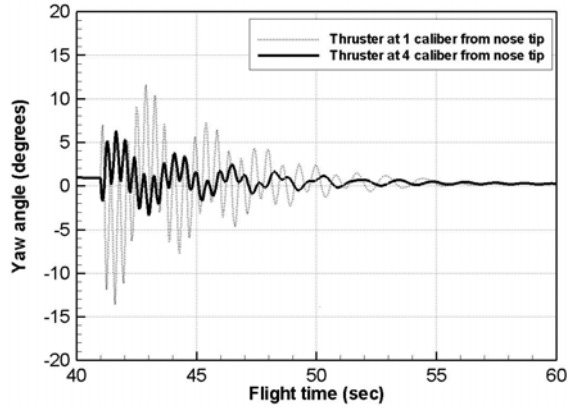


Figure 6. Yaw angle variation with flight time following the ignition of a 20 Ns impulse thruster located on the port side of the projectile.

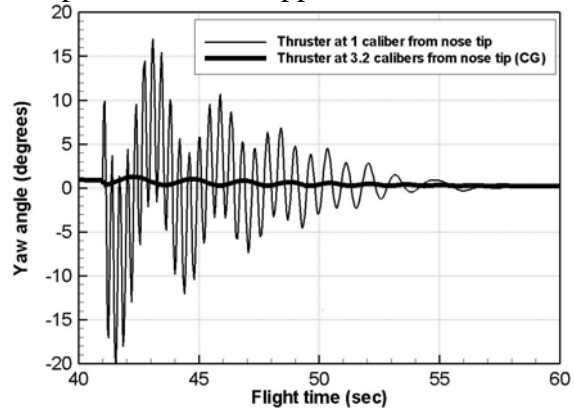


Figure 7. Yaw angle variation with flight time following the ignition of a 30 Ns impulse thruster located on the port side of the projectile.

the center of gravity or slightly aftward. Knowing that information, additional simulations were performed in order to determine the optimum burning intensity of the impulsers in terms of drift correction. Figure 8 presents drift correction generated by a single impulser, located 4 calibers from the nose tip, on the port or starboard side of the projectile as a function of the impulse thruster burning intensity. The results indicate that the variation in the drift correction is more or less linear with the impulse thruster intensity. It also appears that an impulse thruster with a burning intensity of 15 Ns could yield acceptable course corrections in relation to the observed DEP at 10000 m while minimizing the yaw and pitch cycle perturbations.

Another important consideration pertaining to the drift correction achieved is the remaining time of flight to impact at the triggering of the impulse thruster. Figure 9 shows the drift correction that can be expected from a 20 Ns impulse thruster fired for varying length of time before the impact. As expected, for impulse thrusters detonated a very short time before the impact, the drift correction is very limited. Therefore, late in the trajectory, the impulsers can be used to make fine adjustment to the final impact point. On the other hand, for impulsers triggered at 10 or more seconds from the impact time, a non-trivial drift correction is obtained.

Up to this point, the emphasis has been placed on the effect of a single impulse thruster on the drift correction. However, once implemented on an actual artillery projectile, several impulse thrusters will be placed inside the shell in a ring-like fashion. Thus, by detonating more than one impulser along the projectile trajectory, it will be

possible to achieve much greater course correction. This can be seen from Figure 10 which shows the drift trajectory of a 105 mm projectile as a function of range. Trajectories are shown for the cases where no impulse thrusters were used and for the cases where 1, 2, 3, 4 and 5 20 Ns impulse thrusters were detonated. Each impulser yields an additional drift correction of about 50 m. The five impulsers are triggered at flight times of 41.0, 42.3, 42.7, 44.0 and 44.3 seconds respectively. The detonation time of the first impulser was determined arbitrarily. However, the triggering time of impulsers 2, 3, 4 and 5 was based on the magnitude of the drift velocity. Whenever, the

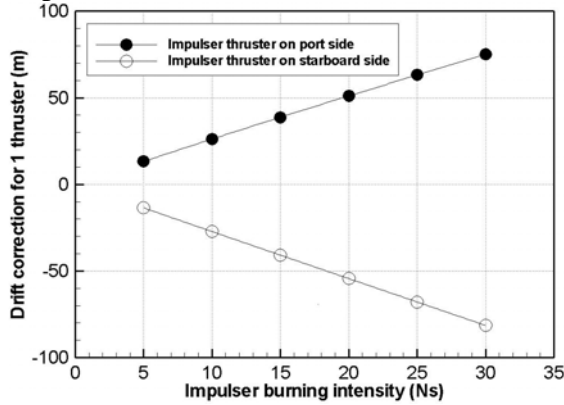


Figure 8. Drift correction obtained for one impulse thruster located at 4 calibers from the nose tip as a function of the burning intensity and triggered at a flight time of 41 s.

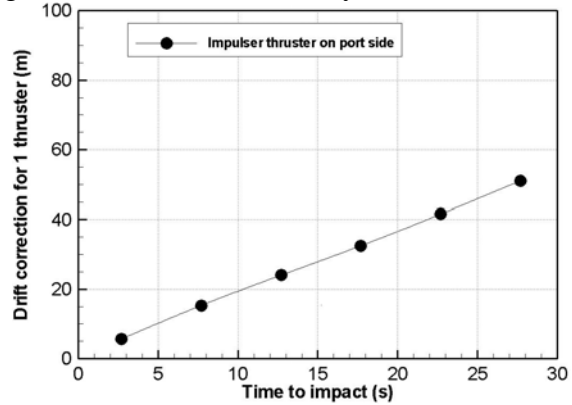


Figure 9. Drift correction obtained for one 20 Ns impulse thruster located at 4 calibers from the nose tip as a function of the remaining flight time at the impulser triggering time.

velocity reached a maximum in the direction of the correction, the next impulser was fired as shown in Figure 11. This procedure was found to maximize the displacement produced by the impulsers. A summary of the effect of the successive impulser detonations on the trajectory of the projectile is shown in Table 1.

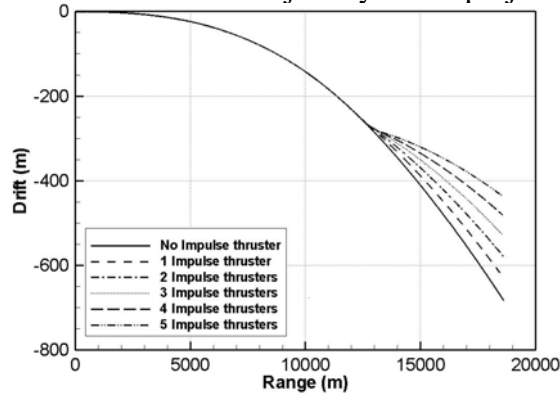


Figure 10. Drift as a function of range for a varying number of 20 Ns impulse thrusters detonated on the starboard side of the projectile at 4 calibers from the nose tip.

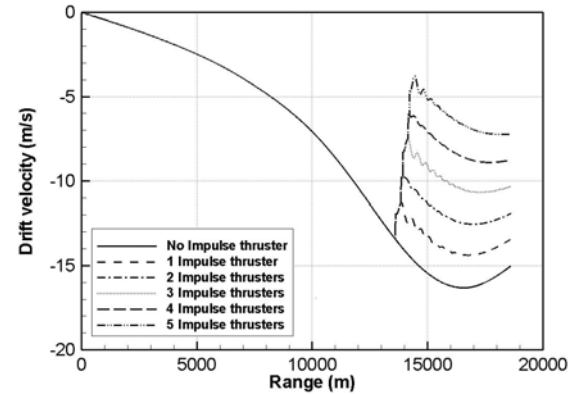


Figure 11. Drift velocity as a function of range for a varying number of 20 Ns impulse thrusters detonated on the starboard side of the projectile at 4 calibers from the nose tip.

Table 1. Effect of successive impulsers on the trajectory of the 105mm projectile.

Number of Impulse Thrusters	Lost Range (m)	Drift Correction (m)	Maximum AOA (degrees)
1 impulser	14.8	54.4	5.9
2 impulsers	12.0	104.2	5.8
3 impulsers	29.8	154.8	6.7
4 impulsers	40.3	202.0	7.0
5 impulsers	71.1	247.8	10.0

CONCLUSIONS

6-DOF simulations were performed on a 105 mm C132 artillery projectile using the CONTRAJ module of PRODAS. The objective of this study was to determine the impulse thrusters' configurations that yield the best control authority and thus the greatest amount of correction on the projectile trajectory. Results indicate that locating the impulse thruster at or aft of the center of gravity provide greater drift correction for a given impulse magnitude. Reasons for this behaviour were explained. It is also shown that impulse thrusters with a burning intensity between 15 and 20 Ns would provide adequate course correction for a 105 mm artillery projectile. The use of several impulse thrusters along the trajectory of the projectile was investigated and shown to increase significantly the amount of correction achieved in drift.

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