AIAA SciTech Forum
6-10 January 2020, Orlando, FL
AIAA Scitech 2020 Forum

10.2514/6.2020-1960

Guided Hard-Launch Munitions: Enabling Advanced Air to Ground Combat

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Guided hard-launch munitions may be implemented on a number of aerial platforms to provide increased weapon system performance in air to ground combat scenarios. This study models a family of medium caliber guided hard-launch systems as a retrofit to existing aerial platforms. Using the patent pending MASS system as an enabling technology for guided aerial gunnery, increased range and total kinetic energy on target is demonstrated for the AH-64 Apache and F-35/A Lightning II. The systems are then juxtaposed with the performance of conventional attack aircraft such as the A-10 Warthog. With the guided aerial gunnery technology, equivalent energies on target at increased range were noted for both systems albeit smaller in caliber. The case study is then extended to demonstrate increased lethality and target engagement capability with systems carrying less than 200 rounds. The potential implications for future airframe design are outlined, demonstrating equivalent mission capability with fewer internal and external weapon stores which decrease overall size and operation cost of new airframes.

I. Nomenclature

C_D = *drag coefficient*
$C_{L\alpha}$ = *derivative of lift coefficient with respect to angle of attack*
$C_{l\delta}$ = *rolling moment due to fin deflection*
C_{lp} = *spin damping moment coefficient*
$C_{M\alpha}$ = *derivative of moment coefficient with respect to angle of attack*
$C_{M\dot{\alpha}}$ = *component of pitch damping moment coefficient due to angle of attack rate*
$C_{Mp\alpha}$ = *magnus moment coefficient*
C_{Mq} = *component of pitch damping moment coefficient due to pitch rate*
$C_{NP\alpha}$ = *magnus force coefficient*
$C_{N\dot{\alpha}}$ = *component of pitch damping coefficient due to angle of attack rate*
C_{Nq} = *component of pitch damping coefficient due to pitch rate*
D = *projectile diameter*
E_T = *rifling energy*
F = *general force acting on body*
F_T = *rifling force*
g = *gravitational acceleration*
H = *total angular momentum*
h = *angular momentum divided by transverse body moment of inertia*
I_x = *body axial moment of inertia*
I_y = *body transverse moment of inertia*
k = *body radius of gyration*
ℓ = *length from base of barrel to projectile base*
M = *general moment acting on body*
m = *projectile mass*
P_h = *probability of hit*

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P_k = *probability of kill*
p = *axial spin*
S = *maximum caliber area*
t = *time*
V = *projectile velocity with respect to earth fixed coordinates*
v = *projectile velocity with respect to wind axis*
$\bar{x}$ = *body unit vector*

α = *angle of attack*
α_r = *barrel rifling angle*
δ_F = *fin deflection angle*
Λ = *Coriolis acceleration*
ρ = *atmospheric density*

II. Introduction

Guided hard-launch munitions are an enabling technology for improved performance on a variety of systems. When deployed as indirect fire these rounds experience flight at higher altitudes, taking advantage of reduced atmospheric density, and therefore, drag. This environmental effect coupled with improved guidance capability for ever smaller weapon systems lends great potential improvements to air to ground combat in both direct and indirect fire scenarios.

A. Guided Hard-Launch Munitions

Aerial guided hard-launch munitions, or guided aerial gunnery, is new only to the aviation community. Guided hard-launch systems have been in service in US forces since the 1970s. Early incarnations such as the 155mm M712 Copperhead were designed for, and still used by, ground forces to improve the range and accuracy of these weapon systems. Modern incarnations of this family of guided artillery such as the 155mm M982 Excalibur are able to effectively interdict targets beyond 20 miles (Ref. [1]). Small caliber guided hard-launch systems have also been developed to improve the accuracy of small arms fire. The Extreme Accuracy Tasked Ordnance (EXACTO) underwent successful testing as a guided 0.50 caliber sniper round. The configurations of these guided projectiles are varied, with many implementing missile-like tail guidance or some combination of canard/wing/tail surfaces for stability and control, though other configurations such as actuated nosecone, aerospike, bang-bang control with pressurized gas, etc. are also possible. Advancements in actuation schemes designed to survive the gun launch event (which can exceed 100,000g's) have allowed this family of munitions to achieve ever greater levels of volumetric compression while decreasing energy consumption during guidance to target. Many of these developments center on adaptive actuation concepts, employing piezoelectric ceramics or shape memory alloys to achieve high bandwidths or deflections respectively (Ref. [2]). The rounds analyzed in this study are fin stabilized and achieve actuation through the deflection of these tail surfaces along two orthogonal axes. An example geometry is shown with a traditional penetrator round (not to scale) in Figure 1.

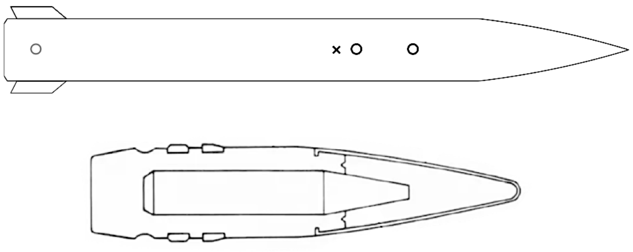

Figure 1: Fin Stabilized Tail Guided Round with Conventional Penetrator Round with High Density Core

The munitions analyzed in this study take advantage of patent pending MASS technology. This system significantly reduces the free flight drag of a given projectile mass when fired from an airframe (Ref. [3]). MASS munitions allow the guided gunnery projectiles such as those shown in Figure 1 to be used as a retrofit in existing gun geometries. To account for the changing geometries and masses involved, an energy analysis is used to ensure that the equivalent gun energy of a given system is maintained across the various incarnations of the guided munitions.

B. Air-to-Ground Combat

Air to ground combat traditionally implements a variety of weapon systems encompassing gunnery, gravity weapons, and missile systems. This study focuses on the potential improvement of the gunnery system to reduce the required internal and external stow volume of gravity and soft-launch systems. Gunnery in particular is more volumetrically efficient as shells have a higher packing factor than both conventional gravity weapons and missile systems. These conventional soft-launch systems require internal bay/doors/trapeze or external pylons that interrupt clean airflow, drive up parasite, profile and interference drag and dramatically boost radar cross-section. The air to ground combat that serves as the focus of this study simulates engagements such as those common to the A-10 Thunderbolt II, a 30mm strafing platform that serves as the backbone for US fixed wing attack aircraft capability. Engagements typically occur at low altitude with the gun system employed against a variety of hard and soft targets.

III. Combat Modeling

The flight dynamics of these bodies were simulated in MATLAB and the terminal intercept capability was used in the case study for the determination of probability of kill (P_k) and probability of hit (P_h). Terminal engagements were simulated with a continuous Von Karman gust model in Simulink at a range of 3.2 km

A. Exterior and Terminal Ballistics

The flight of the projectile following barrel exit is simulated using a six degree of freedom rigid body model based on standard equations of motion. These may be derived from the force and moment balance on the body shown in Eq. 1 and Eq. 2.

$$m\left(\frac{d\bar{v}}{dt}\right) = m\bar{g} + \bar{F}_{aero} \tag{1}$$

$$\frac{d\bar{H}}{dt} = \bar{M}_{aero}\ ; \quad \text{where: } \bar{H} = I_x p\hat{x} + I_y\left(\hat{x} \times \frac{d\hat{x}}{dt}\right) \tag{2}$$

For a given body geometry and composition, the non-dimensionalized coefficients and stability derivatives defining flight may be estimated with a combination of theory and empirical data as found in (Ref. [4]- [5]). With these data, the equations of motion for an axisymmetric, unpowered projectile is written in Eq. 3 and Eq. 4 (Ref. [6]).

$$\begin{aligned}\frac{d\bar{V}}{dt} = \frac{1}{2m}\{&-\rho v\bar{v}SC_D + \rho SC_{L\alpha}[v^2\bar{x} - (\bar{v}\cdot\bar{x})] - \rho SDC_{Np\alpha}\left(I_x/I_y\right)(\bar{h}\cdot\bar{x})(\bar{x}\times\bar{v}) \\ &+\rho vSD\left(C_{Nq} + C_{N\dot{\alpha}}\right)\left(\bar{h}\times\bar{x}\right) + 2m\bar{g} + \bar{\Lambda}\}\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{d\bar{h}}{dt} = \frac{1}{2}\{&\rho vSD^2C_{lp}\left(\bar{h}\cdot\bar{x}\right)\bar{x}/I_x + \rho v^2SD\delta_F C_{l\delta}\bar{x}/I_y + \rho vSdC_{M\alpha}(\bar{v}\times\bar{x})/I_y \\ &+\rho SD^2C_{Mp\alpha}\left(\bar{h}\cdot\bar{x}\right)(\bar{v} - [\bar{v}\cdot\bar{x}]\bar{x})/I_x + \rho vSD^2\left(C_{Mq} + C_{M\dot{\alpha}}\right)\left(\bar{h} - \left[\bar{h}\cdot\bar{x}\right]\bar{x}\right)/I_y\}\end{aligned} \tag{4}$$

Terminal ballistics, referencing the phenomenon associated with target impact and rapid deceleration of the body, is estimated in this study using simple energy methods. High explosive incendiary rounds (HEI) rely upon the stored chemical potential carried within the projectile to interdict a target. Penetrator rounds typically rely upon the kinetic potential of the round at impact and the shaping of the penetrator to achieve a desired probability of kill. For this reason, the P_k of a round configuration and composition is critical to assessing the effectiveness of the system as a whole. For the purposes of this case study, penetrator rounds are modeled as a function of kinetic energy at impact while HEI rounds are designed to carry the same mass of HEI as the system equivalent conventional round. The P_k of the round is then scaled from a known value for the PGU-28 (Ref. [7]) as a function of both projectile mass and target mass (Ref. [8]).

Determination of circular error probable (CEP) was analyzed using a Monte-Carlo type simulation of a simple optimal guidance scheme for these rounds. The methods outlined in (Ref. [9]- [10]) were used to simulate the terminal intercept of these rounds against a variety of stationary and moving targets when accounting for atmospheric effects such as gusts.

B. Interior Ballistics and Gunnery Design

With the implementation of the MASS system, the fin stabilized guided munitions are compatible with existing gun cartridges and feed systems. To account for the variance in composition and geometry during the firing event, a simple energy balance was used. Namely, the muzzle energy of the system upon barrel exit was computed for a conventional round, and then that same energy was applied to the modified MASS guided projectile. The muzzle velocity of a given round therefore, is proportional to the root of the masses of the system (Ref. [8]) if retrofitting the technology to existing platforms for an equal comparison basis.

When designing a gunnery system for use with these fin stabilized munitions, it is desirable to use a smooth bore barrel to reduce the spin upon muzzle exit. Smoothbore systems also have an additional increment in muzzle velocity as there is no longer energy imparted to spin the projectile at a certain rate and blowby is often reduced to a negligible level. The energy lost due to rifling is estimated by integrating the rifling force imparted to the projectile over the length of the barrel. Reference [11] outlines one means of estimating the rifling force, Eq. (5). The subsequent energy increment for a given barrel and chamber velocity and pressure by exchanging the barrel with a smooth bore may then be determined in Eq. (6).

$$F_T = (k/(D/2))^2 F_p \tan(\alpha_r) \tag{5}$$

where: $F_p = \frac{\pi}{4} D^2 P(\ell)$

$$E_T = \int_0^{\ell} \pi k^2 P(\ell) \tan(\alpha_r) \tag{6}$$

For a known chamber pressure distribution as a function of projectile travel down the barrel (ℓ), this quantity may be readily calculated and added to the nominal muzzle energy of a projectile fired from a rifled barrel as a first approximation for a smoothbore variant.

IV. Guided Munitions Performance

Using the equations of motion and muzzle exit conditions described in Section III, a series of fin stabilized projectiles of varying geometries were simulated in a direct fire attack environment. Case studies of launching airframes included the AH-64 Apache and F-35/A Lightning II firing from the M230 chain gun (Ref. [12]) and GAU-22/A (Ref. [13]) respectively. The combat environment includes direct fire engagement at an altitude of 300 m. Nominal effective range was estimated at the point at which the rounds experience tumble when entering the subsonic flight regime. This measure of round effectiveness was validated with the known effective range of the M789 fired from the M230 chain gun. Conventional munitions were first analyzed, then the equivalent guided hard-launch rounds of the same total HEI (high explosive incendiary) mass were compared. The results of this study when implemented on the AH-64 Apache and F-35 platforms are shown in Table 1.

Table 1: HEI Munition Performance

PLATFORM	STANDARD LOADOUT	SIMULATED EFFECTIVE RANGE	MASS GUIDED HARD-LAUNCH RANGE	PERCENT INCREASE
AH-64	940 rounds 30mm	1500 m (Ref. [14])	3300 m	120%
F-35A	180 rounds 25mm	2300 m	3800 m	65%

The HEI rounds analyzed implemented the patent pending MASS technology to significantly decrease the drag of the projectiles in free flight. This system showed the most significant increase in effective range when implemented on the Apache platform as the initial muzzle velocity of the conventional rounds was lower; therefore, the projectiles experienced flight in a higher drag coefficient Mach range for extended periods of time.

The second series of studies focused on the penetrator rounds for each of these systems. Here, the conventional round performance for the combat conditions above were juxtaposed with guided systems assuming the cartridge and gunnery system were compatible. The additional increment in muzzle velocity associated with a change from rifled to smooth bore barrels was then studied and the results shown in Table 2. The energy imparted to the target is compared with that of the A-10 penetrator located within the PGU-14 30mm round (Ref. [15]).

Table 2: Penetrator Munition Performance at 1500 m

PLATFORM	CONVENTIONAL ENERGY ON TARGET	MASS ENERGY ON TARGET	ETARGET/ETARGET,A10 VS. ETARGET,MASS /ETARGET,A10
AH-64	10.5 kJ	54.4 kJ	16% | 85%
AH-64 SMOOTHEBORE	N/A	61.3 kJ	N/A | 96%
F-35A	31.3 kJ	64.7 kJ	38% | 82%
F-35A SMOOTHEBORE	N/A	68.6 kJ	N/A | 107%

The penetrator rounds, when equipped with guidance implementing the MASS system, showed significant increases in kinetic energy on target. In the case of a barrel retrofit on the AH-64 and F-35, the MASS penetrator rounds were able to nearly match the A-10 kinetic energy on target. This increase in effective energy on target is also equivalent to an extension in effective range of the projectile—demonstrated in Figure 2. Here, the additional energy of the penetrators afforded by decreases in drag during the exterior ballistic flight regime results in a flattened fire trajectory. When coupled with round guidance, it has been demonstrated that these rounds have the capability of also reducing circular error probable (CEP) by an order of magnitude at these extended ranges (Ref. [9]).

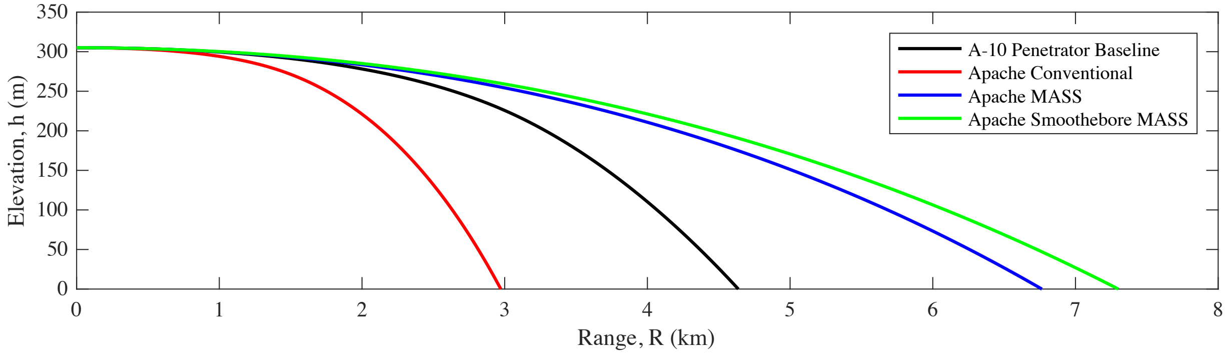

Figure 2: Trajectories of Guided Gunnery for Direct Fire

V. F-35 Case Study

The potential improvement in the ground attack capability of the F-35A using the GAU-22/A 25mm Gatling system was investigated using the methods described in this paper and juxtaposed with the A-10 system capability. As demonstrated in Section IV, it is possible to match the 30mm A-10 energy on target with a smoothbore guided MASS 25mm retrofit of the F-35 GAU-22/A at 1500 m. This result is then extended to show mission capability by performing a statistical analysis of miss radii using the methods discussed in (Ref. [9]). The $P_h * P_k$ of the conventional PGU-14 fired from the A-10 at a range of approximately 2 miles was extracted assuming 0.5 seconds of fire was needed to interdict a nominal ground target (Ref. [16]). In this case, it is assumed the ground vehicle is armored and in the 18,000 kg weight class. The 25mm MASS guided munition by comparison is a high-density tungsten tail guided penetrator round compatible with the existing 219mm cartridge. The 95% CEP of this round falls within 1.0 m, indicating the guided round achieves a kinetic impact for nearly all ground vehicle type targets. The number of rounds to achieve a kill probability of 95% is then compared across these platforms, and the maximum probable targets engaged given conventional loadout capability is illustrated in Table 3.

Table 3: F-35/A Ground Attack with Guided MASS (Ref. [16])

PLATFORM	STANDARD LOADOUT (ROUNDS)	P_K*P_H	PROJECTILES TO ACHIEVE 95% P_K	MAX TARGETS ENGAGED
A-10 PGU-14	1174	0.08	35	34
F-35/A PGU-25	180	0.05	59	3
F-35/A GUIDED MASS 25MM	180	0.34	8	25

The implications for ground attack airframe design is readily apparent in this case study. An effective increase in caliber is observed by taking advantage of guided hard-launch systems, with 25mm systems providing the same energy on target as conventional 30mm systems at extended ranges. The guidance lent to these weapon systems also significantly reduces CEP such that the maximum number of targets for a given loadout may be increased. Here, it was demonstrated that without redesign of the airframe or major components, the F-35/A is capable of interdicting nearly as many targets as the A-10 although equipped with far fewer rounds and a smaller gun platform. Future airframes may therefore require less internal volume and/or external hardpoints dedicated to other weapon types or larger caliber systems, shrinking the size of the aircraft and decreasing cost and airframe complexity.

VI. Conclusions

The implementation of guided hard-launch munitions on aerial platforms allows for significant increases in system capability in ground attack missions. By implementing the MASS system as a technology enabler for round guidance, without significant modification to the gunnery system, effective increases in caliber are achieved with both a retrofit of the Apache and F-35/A, achieving near A-10 like energy on target impact. With the reduction in CEP afforded by lending guidance to these medium caliber munitions, significant increases in P_h are made possible, increasing the effectiveness of a given round while increasing the number of targets potentially engaged for a conventional weapon systems loadout. This has implications for new airframe design by decreasing the amount of internal and external stowage required onboard a given aircraft to achieve nominal mission capability.

Acknowledgments

The authors would like to thank the University of Kansas aerospace engineering department for the use of their facilities to support this research. Additionally, the authors would like to thank the Madison and Lila Self Graduate Fellowship for the sustained support at the University of Kansas.

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