

A De-Spin and Wings-Leveling Controller for a 40 mm Hybrid Projectile

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ABSTRACT

A Hybrid Projectile (HP) is a round that transforms into a UAV after being launched. Some HP's are fired from a rifled barrel and must be de-spun and wings-level for lifting surfaces to be deployed. Control surfaces and controllers for de-spinning and wings-leveling were required for initial design of an HP 40 mm. Wings, used as lifting surfaces after transformation, need to be very close to level with the ground when deployed. First, the tail surface area needed to de-spin a 40 mm HP was examined analytically and simulated. Next, a controller was developed to maintain a steady de-spin rate and to roll-level the projectile in preparation of wing deployment. The controller was split into two pieces, one to control de-spin, and the other for roll-leveling the projectile. An adaptable transition point for switching controllers was identified analytically and then adjusted by using simulations. The initial roll position may never be the same due to the round being inserted into its launch tube at any roll angle, therefore an adaptable method was used to shorten the time required to become wings-level. An aerodynamic model was constructed, in house, in Simulink using a 6 DoF simulator. Aerodynamic data from literature sources was collected and tail forces and moments were estimated. Each tail was assumed to have an adjustable local angle of attack for increased moment generation during de-spin and fine control during roll-leveling. Results show that the round can be expected to de-spin in 4%, wings-level in 5%, and be ready for wing deployment in a maximum 10% of flight time.

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INTRODUCTION

A Hybrid Projectile (HP) is a round that transforms to an unmanned aerial vehicle (UAV) after being launched [1]. West Virginia University's (WVU) Mechanical and Aerospace Engineering department is currently working on development of several HP rounds to extend range and have the capabilities to maneuver.

Spin-stabilized projectiles must remain spinning after being launched because they are dynamically unstable. Being dynamically stable causes the projectile, when it is disturbed from a steady state, to return gradually to its original state. The center of pressure of the projectile is forward of the center of gravity, causing them to pitch up with a positive angle of attack, making the projectile tumble.

Control surfaces can be added to a projectile to move the aerodynamic center aft of the center of gravity. By moving the aerodynamic center a projectile can be de-spun while still remaining stable.

Different methods for controlling projectiles are available [2]. A technique derived by F. Fresconi et al. [3] applies a paddle to a spinning projectile that can be deployed at a specific angle to create an aerodynamic asymmetry, which creates a maneuver. Flow jets have also been considered for control because of their ability to change to flow over certain areas of the projectiles to make maneuvers, as seen in a work by Jubaraj Sahu et al. [4].

A method was sought to have any currently designed spin-stabilized projectile (i.e.; M119 105mm Howitzer, M198 155mm Howitzer, M781 40 mm grenade, etc.) be modified into a dynamically stable projectile that does not require roll to remain stable. Transforming a currently designed projectile will allow the existing launch system to be used. Tail or canard control surfaces and a control system can be used to transform a current projectile into a UAV through a roll leveling maneuver so lifting surfaces can be deployed.

To test this method, a baseline M781 40 mm practice round will be considered in simulation to a hybrid projectile

(HP). This projectile must be de-spun and self-level so that lifting surfaces could be deployed.

METHOD

To begin the process, of adapting a 40 mm round into a HP, it was important to know aerodynamic data and specifications for the baseline projectile. Also, it was imperative to determine the control surfaces that will be used to de-spin and stabilize the projectile. In this case tail surfaces were used because of their tendency to pitch the projectile down as angle attack increases, adding stability. A simple build-up of aerodynamic coefficients was then created to model the flight of the projectile. After the aerodynamic coefficients were determined, the tail sizing was investigated to ensure that the projectile will de-spin in the required time and also remain stable. With control surfaces applied to the projectile, a controller was created to deflect the local angle of attack of the tail surfaces to de-spin and wings-level the projectile. Testing and tuning of this model was done using the 6DoF (Six Degree of Freedom) system in the aerospace blockset of MATLAB Simulink [5].

AERODYNAMIC MODELING

Baseline Coefficients

Aerodynamic forces and moments create forces and moments that act on the projectile are due to the geometry, velocity and orientation to the free stream velocity. The forces and moments can be built from coefficients and divided up for all components of the projectile. A build-up of these aerodynamic coefficients was created to show how all the components of the projectile work together to be able to model the projectile using a simulator.

The aerodynamic forces and moments were split into two categories; longitudinal and lateral. The longitudinal forces and moments were lift, drag and pitching moment. The lateral forces and moments were side force, yawing moment and rolling moment.

The orientation of the projectile consists of angle of attack, α , and sideslip, β , as a deviation from the freestream velocity vector, V_∞ . Angle of attack was the inclination of the nose of the projectile from a side view and sideslip is the deflection of the projectile nose from a top view, [Figure 1](#). α and β were determined by using the projectile velocity vector in [equations 1](#) and [2](#) [6]. The free-stream velocity vector orientation with respect to the velocity vector of the projectile yields the pitch and sideslip angles. The velocity vector of the projectile consists of x-direction, y-direction and z-direction velocities, u , v and w , respectfully. The total aerodynamic velocity that will be used later in coefficient equations is determined from the magnitude of the body referenced velocity vector, [equation 3](#).

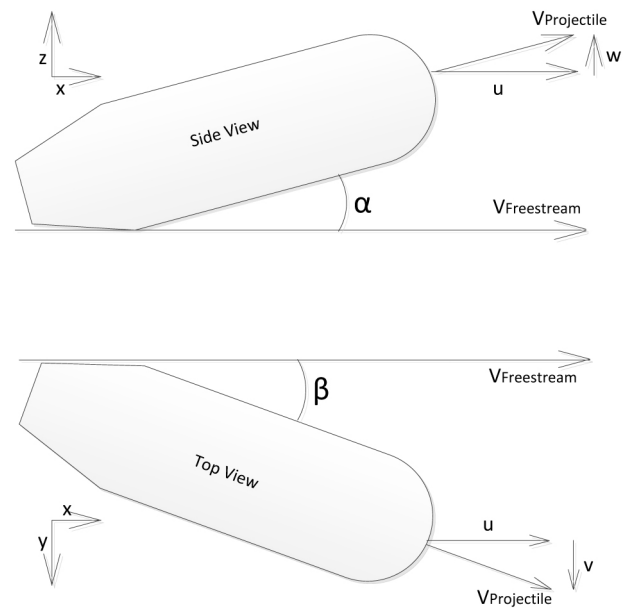


Figure 1. Velocity Vector Breakdown with Pitch and Sideslip

$$\alpha = \tan^{-1} \left(\frac{w}{u} \right) \quad (1)$$

$$\beta = \tan^{-1} \left(\frac{v}{u} \right) \quad (2)$$

$$V = \sqrt{u^2 + v^2 + w^2} \quad (3)$$

Aerodynamic coefficients for the basic 40 mm projectile used in this study were found in literature. The nominal launch velocity of the 40 mm round was found to be 76 m/s, [7]. The drag coefficient was determined as an average of two separate literature sources [3] [8]. Similarly for the lift coefficient, the average of both sources was used [3] [8]. Between the two sources, there was a 1% difference in drag coefficient and 10% difference in lift coefficient. From CFD, the pitching moment coefficient, C_{mp} , was given as -0.0273 [3]. With the “negative” X_a [9] distance for aerodynamic center to center of gravity, the value that will be used for pitching moment coefficient is 0.0273 . The determined pitching moment coefficient with angle of attack was found to be positive since the round is not stable without spinning. Tail surfaces must be added to dynamically stabilize the projectile because lift on a tail surface will cause the angle of attack to decrease. The pitch damping coefficient due to pitch rate, q , was found in a report [10] as -0.1 . The baseline coefficients used are compiled in [Table 1](#).

Table 1. Baseline 40-mm Grenade Coefficients

C_{D_0}	0.2775
C_{L_α}	0.0378
C_{m_α}	0.0273
$C_{M_{\dot{q}}}$	-0.1

Coefficients Added with Tails

Drag

Adding tails to a projectile changes the aerodynamic forces and moments. These changes were accounted for by adding coefficient components of the tails. These added aerodynamic coefficients from the tail can exhibit similar behavior to a real projectile, but make it quicker to evaluate a large array of design configurations.

The drag addition from tail surfaces was determined first. It was assumed that the tail surfaces that will be used will be thin tails, which can be assumed as flat plates. The drag of the tail was compiled of its parasite drag as well as drag with change in deflection. The parasite drag was calculated by using the skin friction drag of a turbulent flat plate, [equation 4](#), as given by Prandtl and found in text [\[11\]](#). The lift induced drag by the tails causes an increased drag coefficient due to the magnitude of α , β and δ , [equation 5](#). δ in [equation 5](#) is the tail deflection made by the roll controller and must be multiplied by two since the C_{L_α} equation is used for two tails and four tails will be deflected for de-spin and wings-leveling. The drag coefficient build-up compiled in [equation 6](#) includes a value 2 with the number of tails, N, for the two sides of a flat plate [\[11\]](#).

$$C_{D_{0 \text{ tail}}} = \frac{0.058}{Re_L^{1/5}} \quad (4)$$

$$C_{Di} = \frac{[C_{L_\alpha}(|\alpha| + |\beta| + 2|\delta|)]^2}{\pi e AR} \quad (5)$$

$$C_{D \text{ Total}} = C_{D_0} + C_{D_{0 \text{ tail}}} \left(\frac{2NA_{\text{tail}}}{A_{\text{ref}}} \right) + C_{Di} \quad (6)$$

Lift

The lift addition due to the tail surfaces was determined next. The zero angle of attack lift coefficient and lift with change tail deflection were examined. The lift of the tail with zero degrees of tail deflection is, $C_{L_0}=0.0$, since the tail surfaces are assumed as flat plates, with no camber. The lift coefficient of the tail with tail deflection is given by [equation 7](#), which takes into account the aspect ratio of the tail surfaces, as given by Prandtl lifting-line theory. The build-up of the total lift coefficient, [equation 8](#), was compiled using a similar set-up as in Mechanics of Flight [\[6\]](#).

$$C_{L_{\alpha \text{ tail}}} = \frac{2\pi}{(1 + (2/AR_{\text{tail}}))} \quad (7)$$

$$C_{L \text{ Total}} = C_{L_\alpha}(\alpha) + C_{L_{\alpha \text{ tail}}} \left(\alpha \left(\frac{\pi}{180} \right) \right) \left(\frac{NA_{\text{tail}}/2}{A_{\text{ref}}} \right) \quad (8)$$

Pitching moment

The pitching moment added by adding tails are the pitching moments created by the projectile spinning and the tail surfaces having an effective angle of attack. Both of these additional coefficients were found in [\[12\]](#). The pitching moment due to tails being deflected, [equation 9](#), is determined from the flat plate lift with tail efficiency, η . The tail efficiency used was 90% which was assumed for boundary layer effects. The pitching moment due to the roll rate of the projectile, [equation 10](#), was added because of the recovery moment created to drive the projectile to zero degrees angle of attack. In the build-up of the pitching moment coefficient, [equation 11](#), the pitching moment from roll rate, p , of the tails is multiplied by the sign of the angle of attack because of its tendency to pitch down with a positive α and pitch up with a negative α .

$$C_{M_{\alpha \text{ tail}}} = \frac{-\eta 2\pi}{(1 + (2/AR_{\text{tail}}))} \quad (9)$$

$$C_{M_{p \text{ tail}}} = \frac{-(\eta(.6)NA_{\text{tail}}l_t^3)}{A_{\text{ref}}d} \left(\frac{p^2}{V^2} \right) \quad (10)$$

$$\begin{aligned} C_{M \text{ Total}} &= C_{M_\alpha}(\alpha) + C_{M_{\alpha \text{ tail}}} \left(\left(\frac{\alpha\pi}{180} \right) \right) \left(\frac{l_{\text{tail}}}{l_{\text{ref}}} \right) \left(\frac{NA_{\text{tail}}/2}{A_{\text{ref}}} \right) \\ &+ C_{M_{p \text{ tail}}}(\text{sign}(\alpha)) + C_{M_{\dot{q}}} \left(\frac{(180/\pi)qd}{2V} \right) \end{aligned} \quad (11)$$

Side force

The side lift force refers to the force in the y-direction, which is similar to lift in the z-direction. Side lift force coefficient uses the same build up components as lift because the round is symmetric. The only difference to [equation 12](#), from [equation 8](#), is the coefficients are multiplied by β instead of α .

Yawing moment

Similarly, the pitching and yawing moments share the same symmetry, [equation 13](#). However, since there is a difference in beta angle being used in this model as [equation 2](#) and the sideslip angle that Simulink's built in block determines the yaw rate, r , was of the opposite sign