

Roll and Pitch Produced During an Uneven Wing Deployment of a Hybrid Projectile

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ABSTRACT

Uneven wing deployment of a Hybrid Projectile (HP), an Unmanned Aerial Vehicle (UAV) that is ballistically launched and then transforms, was investigated to determine the amount of roll and pitch produced during wing deployment. During testing of an HP prototype, it was noticed that sometimes the projectile began to slightly roll after the wings were deployed shortly after apogee. In this study, an analytical investigation was done to determine how the projectile body dynamics would be affected by the wings being deployed improperly. Improper and uneven wing deployment situations were investigated throughout the course of this study. The first analyzed was a single wing delaying to open. The second was if only one wing was to lock into a positive angle of incidence. The roll characteristics when both wings were deployed but only one was locked into an angle of incidence resulted in a steady state roll rate of 4.5 degrees per second. It is imperative to ensure that an HP wing deployment mechanism must be designed to deploy as evenly as possible.

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INTRODUCTION

The Hybrid Projectile (HP) is a class of projectiles that transforms into Unmanned Aerial Vehicles (UAVs) after launch and then can maneuver and glide, gaining the projectile controllability and range extension [1]. Thus far, research at West Virginia University (WVU) has been conducted to determine aerodynamic aspects, perform basic launch and flight testing, flight simulations, expected range extension, and performance of 40 mm and 60 mm projectiles based on existing US Army practice munitions. Initial wind tunnel experiments were performed to understand the aerodynamic contribution of wings protruding and opening from a projectile body [2], but the effects of uneven wing deployments were not fully investigated. Several initial designs of an HP-60 mm were test fired and it was noticed that roll was induced shortly after wing deployment as the HP was upside down. To address this issue, an investigation was performed on an HP of similar design to better understand the effect of uneven wing deployment and thus their locking into an angle of incidence.

A relationship between the projectile's final destination and the impact on range extension due to uneven wing deployment was performed by first iteratively calculating the lift, drag, pitch, and roll coefficients generated by a deploying wing and then using this information in a flight simulation model.

For this study, an HP was considered that was based on the M781 40mm practice round, but was modified to include internally stowed wings and was identified as an HP-M781.

During wing deployment, the velocity, area, and wing shape were used to calculate the coefficients of lift, drag, pitch, and roll produced by both wings and their resultant impact on the projectile's ballistic path.

This study examines the case of a single wing deploying and then the other opening and where only one of the wings locks into an angle of incidence. These situations were focused upon because other scenarios, such as only a single wing opening, are understood to be completely detrimental to performance.

DELAYED WING DEPLOYMENT

The first step in determining the effects of an uneven wing deployment was to find M781 aerodynamic coefficients. Next, expressions were developed for how wings will create forces and moments on the body of the projectile. The standard M781 aerodynamic coefficients were found in literature [3] and initial conditions for simulation are listed in [Table 1](#). Simulations were performed using the HP 6DoF system [4] that allows coefficients of bodies, with area references to the nose area, to switch to different sets effectively simulating the wings deploying.

Wings of the HP-M781 deploy shortly after apogee as the body enters the proper glideslope. Until apogee, the projectile is following a ballistic trajectory, therefore in order to shorten simulation times, it was advantageous to start the projectile at apogee. The apex of flight was determined to be 53% of its

maximum range, at 203.2 meters altitude, at a velocity of 43 m/s, and pitch angle of zero degrees. Although the M781 round was designed to be spin-stabilized, the HP-M781 could not be spinning for wing lift to extend range. Therefore, at apogee before the wings open, the round was assumed to not be spinning for this study. The HP-M781 CG was moved forward to maintain static stability within the simulations.

Table 1. HP-M781 Initial Conditions and Parameters

Pitch	70 deg.
Launch Velocity	76 m/sec
Diameter	40 mm
Length	133 mm
Mass	0.199 kg
Roll Rate	0 deg/sec
Wing Length (R)	100 mm
Operating Reynolds Number	~100k
$C_{D_{Body}}$	0.2775
$C_{L\alpha_{Body}}$	0.0378
$C_{m\alpha_{Body}}$	-0.0273

CALCULATE TRANSIENT EFFECT OF WING DEPLOYMENT

The roll angle of the projectiles body with respect to the ground during wing deployment can directly affect the destination of the round. A body roll with wings will most likely induce a heading turn. In order to determine the roll angle as the wings deploy, the rolling acceleration needed to be calculated with respect to the wing rotational position. The rolling angular acceleration ($\dot{p}$), about the x-axis, was calculated using Equation (1), where τ is the rolling torque from the wings and I_{xx} is the rolling moment of inertia.

In Equation (1) [5], the rolling torque was continuously changing as the wing was deployed and was modified to a discrete time step, Δt , so that the angular acceleration could be calculated. From angular acceleration, the roll rate and roll angle could be determined from the time step. The subscript "i", in Equations (1), (2), (3), was used to show the values being solved at each time step. Equation (2) is the roll rate, p , of the projectile and Equation (3) is used to determine the roll angle, ϕ .

$$\dot{p}_i = \frac{\tau_i}{I_{xx}} \quad (1)$$

$$p_i = p_{i-1} + \dot{p}_i \Delta t \quad (2)$$

$$\phi_i = \phi_{i-1} + p_i \Delta t \quad (3)$$

A similarly sized HP wing mechanism in [2] took 100 milliseconds from release to the final wing position and therefore was used as the deployment time in this study. The time step used was 0.001 seconds to give 0.9 degrees of wing deployment per step. The rolling torque was calculated using Equation (4) [6] and was calculated at each time step, where V_{ref} is the velocity experienced by the wing, A_{ref} is the wing area in the air flow, and C_{ℓ_i} is the rolling moment coefficient.

$$\tau_i = .5\rho A_{ref} V_{ref}^2 C_{\ell_i} \quad (4)$$

The rolling moment, C_{ℓ_i} , was calculated at every time step due to the two contributions from rolling moment of the wings. The first, was due to the lifting force of the wing and the second was rolling drag acting in the opposite direction similar to calculating the rolling moment coefficient in [3].

$$C_{\ell_i} = C_{L_i} \left(R_i \frac{A_i}{A_{ref}} \right) + C_{L\alpha} \frac{A_i R_i}{A_{ref} d} \frac{p_i}{V_i} \left(\frac{p_i \frac{180}{\pi} d}{2V_i} \right) \quad (5)$$

In order to calculate the rolling moment produced from the rolling moment coefficient, the velocity at the wing as it deploys out of the body needed investigated. The wing deployment mechanism starts away from the oncoming flow, reducing the velocity seen by the wing. The wing tip velocity, $u_{wingtip}$ was calculated using Equation (6) where the wing deployment radius, R , wing velocity, u , and the angle of deployment, θ , are shown in Figure 1. The wing tip velocity as the mechanism opens was calculated as $V_i = V_{apogee} - u_{wingtip}$ and is shown as Figure 2.

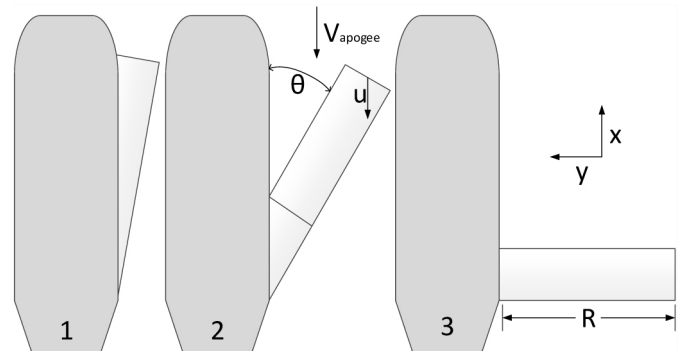


Figure 1. Sketch of Wing Deployment (1) Early Stage, 2) Middle Stage, and 3) Wing Fully Deployed

$$u_{wingtip} = \omega R \cos(90 - \theta)$$

(6)

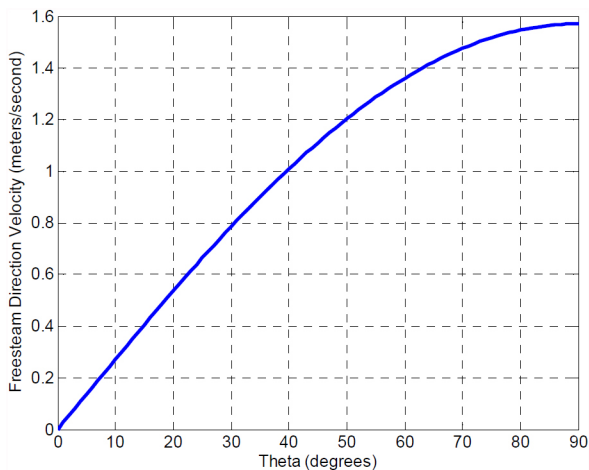


Figure 2. Freestream Wing Tip Velocity During Wing Deployment

Wing tip velocity was calculated in the opposite direction of the freestream due to the wing rotation. The tip velocity needed to then be subtracted from the freestream velocity to estimate the velocity experienced by the wing tips. While this is not physically always true along the entire wing deployment, this estimation was used to simplify the model. Since the wing deployment is approximately at apogee the velocity at apogee used was the freestream velocity. For the projectile investigated in this study, 43 meters per second was used as the apogee velocity.

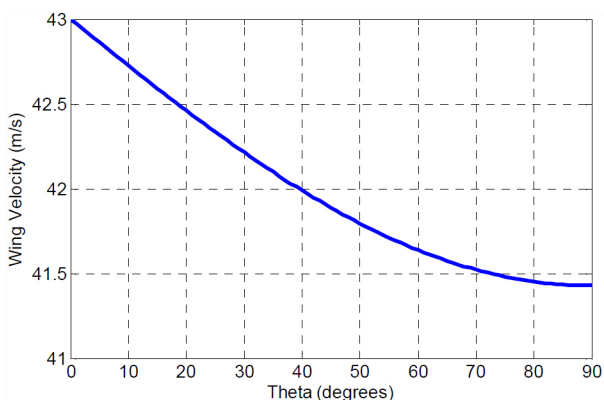


Figure 3. Air Velocity Experienced by the Wing

It must be noted that freestream velocity was modeled to be aligned with the body axis during the simulation. This effectively yields 100 different thickness-to-chord ratio wing sections during the 100-step wing deployment. The next transient variable that was calculated was the area of the wing that was out of the body, experiencing the air velocity. During deployment, the wing area contains a rectangular planform hidden by the body making it unusable for lift production, shown in part 2 of Figure 1. Two separate Equations were used to calculate the wing area outside the body. Equation (7) was used to calculate the wing area before the leading edge has completely cleared the body. In this case Equation (7) was used for 1 to 12 degrees of wing deployment. After the leading

edge clears the body Equation (8) was used to calculate the wing area. The leading edge exits the body at 13 degrees so 13 to 90 degrees of wing deployment was used in Equation (8).

$$A_i = \frac{R^2 \sin(\theta)}{2}$$

(7)

$$A_i = C \left(R - \frac{C \cot(\theta)}{2} \right)$$

(8)

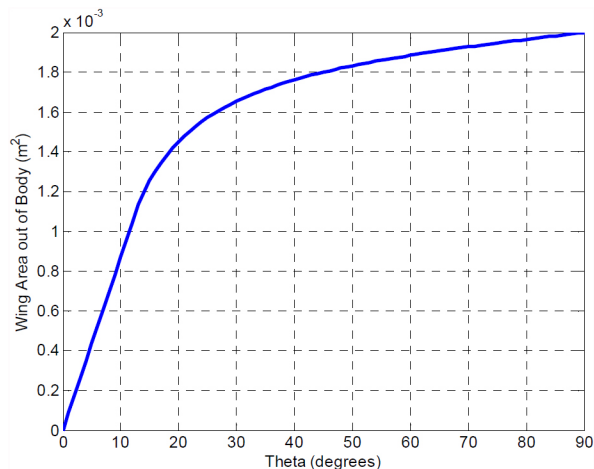


Figure 4. Wing Area Out of the Body as Each Wing was Deployed

At each sweep position the wing has a positive angle, Λ , as it is being rotated out of the body, which reduces its lift coefficient. The sweep angle was calculated at each angle as the wing is being rotated out of the body as $\Lambda = 90^\circ - \theta$. The lift coefficient was then calculated as Equation (9) [2] where C_{L_0} is the zero angle of attack lift coefficient and was found to be 0.2 for the SD6060 airfoil, Figure 5 [1]. As the wings deploy, it was assumed that the angle of attack of the body and the wings would be zero. The short deployment duration combined with the mass properties would not produce much, if any, variation in the angle of attack and therefore C_{D_0} and C_{L_0} at zero degrees was used in the calculations of lift, shown in Figure 6, and drag only during deployment.

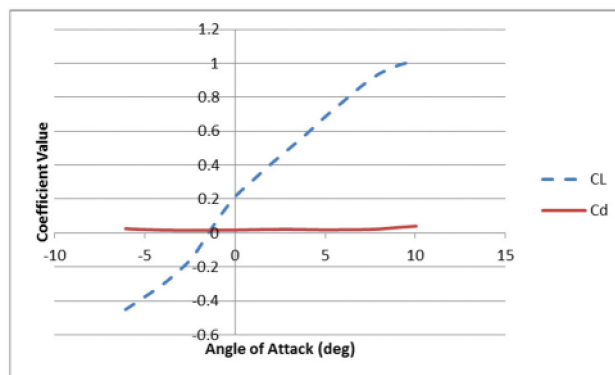


Figure 5. Lift and Drag Coefficient for SD6060 Airfoil [1]