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Mass asymmetry and tricyclic wobble motion assessment using automated launch video analysis

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Abstract

This paper describes an approach to identify epicyclic and tricyclic motion during projectile flight caused by mass asymmetries in spin-stabilized projectiles. Flight video was captured following projectile launch of several M110A2E1 155 mm artillery projectiles. These videos were then analyzed using the automated flight video analysis method to attain their initial position and orientation histories.

Examination of the pitch and yaw histories clearly indicates that in addition to epicyclic motion's nutation and precession oscillations, an even faster wobble amplitude is present during each spin revolution, even though some of the amplitudes of the oscillation are smaller than 0.02 degree. The results are compared to a sequence of shots where little appreciable mass asymmetries were present, and only nutation and precession frequencies are predominantly apparent in the motion history results. Magnitudes of the wobble motion are estimated and compared to product of inertia measurements of the asymmetric projectiles.

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Keywords: Aeroballistics; Artillery; Pitch; Yaw; Epicyclic motion; Tricyclic motion; Video analysis

1. Introduction

All artillery projectiles contain slight mass asymmetries that are caused by a variety of factors including manufacturing tolerances, storage procedures, and the design itself. The M110A2E1 155 mm projectile system contains a payload of white-phosphorous (WP) used to identify impact locations and hinder visibility on the battlefield. Because WP fill has the ability to deform and change shape at high temperatures, all M110A2E1 projectiles are required to be stored upright. If left on their side for prolonged periods of time or at high temperatures, the WP material has the potential to collect on one side of the projectile, resulting in significant mass asymmetries.

The mass asymmetries can be one of two types. The first case is when the center of gravity is located a small distance laterally off the geometric axis of symmetry of the projectile (static imbalance) [1]. This will cause lateral throwoff at muzzle exit. The second case is when the principal axis of inertia is not aligned with the geometric axis of symmetry of the projectile (dynamic imbalance). A dynamic imbalance will result in a small body fixed trim angle and potentially large initial angular motion. The M110A2E1 projectiles in this study have WP collected on one side, resulting in both static and dynamic imbalances.

A symmetric spin stabilized projectile without a dynamic imbalance exhibits what is known as epicyclic motion. In epicyclic motion, the nose of the projectile "cones" around the projectile's velocity vector at two distinct frequencies as

$$\zeta_{\text{balanced}} = K_{\text{F}} e^{i(\varphi 0_{\text{F}} + \dot{\varphi}_{\text{F}} s)} + K_{\text{S}} e^{i(\varphi 0_{\text{S}} + \dot{\varphi}_{\text{S}} s)} \quad (1)$$

where ζ is the magnitude of the pitching motion, K represents the oscillation amplitude, φ_0 represents the phase shift, $\dot{\varphi}$ represents the oscillation frequency, and the subscripts "F" and "S" represent the fast and slow oscillations. The fast oscillation is known as nutation, and the slow frequency is known as precession. Most artillery projectiles have only slight dynamic imbalances, making it possible to accurately model their six degree-of-freedom trajectories using only these two effects (as well as the yaw of repose which affects the trajectory mostly near the maximum ordinate of the trajectory curve).

A projectile with a significant dynamic imbalance will exhibit a third frequency of coning motion following cannon launch. This motion is referred to by McCoy [2] as the "tricyclic" arm but will be referred to as "wobble" in this paper, since wobble is defined as a fluctuating state of motion caused by a mass imbalance. The wobble motion occurs at a frequency that is equal to spin-rate of the projectile. This motion is described in Eq. (2),

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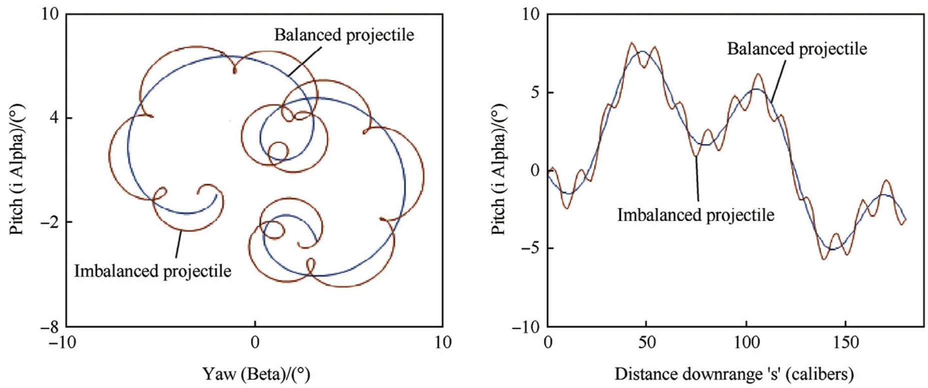

Fig. 1. Epicyclic and tricyclic projectile motion (after Ref. 3).

$$\zeta_{\text{imbalanced}} = K_{\mathrm{F}} \mathrm{e}^{i(\varphi 0_{\mathrm{F}} + \dot{\varphi}_{\mathrm{F}} s)} + K_{\mathrm{S}} \mathrm{e}^{i(\varphi 0_{\mathrm{S}} + \dot{\varphi}_{\mathrm{S}} s)} + K_{\mathrm{w}} \mathrm{e}^{i(\varphi 0_{\mathrm{w}} + ps)} \tag{2}$$

where the subscript w represents the wobble oscillation and p represents the projectile spin-rate. All three “coning” motions rotate the nose of the projectile in the same direction as the spin-rate, which for all U.S. artillery projectiles is clockwise when looking from the base toward the nose. Illustrations of the initial coning motion are shown in Fig. 1 for a projectile with and without a significant dynamic imbalance.

2. Test description

To investigate the effects of improper storage, eight M110A2E1 WP projectiles were stored on their side at hot conditions to induce a mass asymmetry. After their inertial properties were measured, four of the eight asymmetry-induced projectiles were reheated while upright to restore their mass distribution to normal balanced conditions.

In May of 2015, the four re-balanced and four imbalanced projectiles were fired at Yuma Proving Ground, AZ. Launch video for each of these test shots was recorded using two Trajectory Tracker rotating-view high speed optical systems on opposing sides of the azimuth of fire.

3. Data analysis

The launch videos were then analyzed using the automated flight video analysis (AFVA) system [4]. This analysis processes each frame of a launch video to segment the shape of the projectile and identify key points such as the nose, center of gravity (CG) and base locations. The pitching motion history estimated from each camera is then corrected and combined to determine the resolved three dimensional (3D) pitch and yaw motion history for the first ~150 m of flight. A screen shot of the AFVA extracting the projectile shape of an M110A2E1 projectile is shown in Fig. 2.

The resolved pitch and yaw histories from AFVA for rounds with (left) and without (right) dynamic imbalances are shown in Fig. 3.

The next step in the analysis was to isolate the wobble motion from the resolved pitch and yaw histories. To do this, reasonable estimates for the nutation and precession frequencies were determined. For the M483 projectile (which is a ballistic match to the nominal M110A2E1), those values were roughly 72 Hz for the fast arm, 17 Hz for the slow arm, and a spin-rate of 136 Hz for an average muzzle velocity of 420 m/s. Using these values, only the magnitudes and phase shift angles for both the fast and slow oscillation modes needed to be matched to resulting pitching motion history. This was done by first aligning the fast oscillation and then incrementally adjusting the slow oscillation until the difference between the epicyclic fit and the raw pitch data resembled a steady harmonic oscillation. The final step was to fit a sinusoid oscillating at the spin-rate to the isolated wobble motion. This process is illustrated for one of the imbalanced projectiles (which clearly illustrated wobble) in Fig. 4.

The complete results for all eight rounds are shown in Fig. 5. It required several iterations of parameter adjustments to arrive at a best-fit for the epicyclic motion of the projectiles, and it was especially difficult for the projectiles that were restored to normal levels of inertial asymmetry. In addition, all eight of these rounds exhibited a relatively low amount of total pitching motion, making it especially difficult to determine the correct epicyclic parameters. Still, it was possible to isolate the wobble motion for each of the rounds fired. Once isolated, it was clear that the projectiles with mass asymmetries exhibited significantly more wobble motion.

One unexpected benefit of this analysis was that it illustrated the precision of the AFVA method to measure projectile orientation. Previously, it was determined that AFVA measurements were within 0.1° of on-board electronic measurements [5], but clearly the data from this test smoothly show fluctuations in pitching motion much smaller than 0.01°.

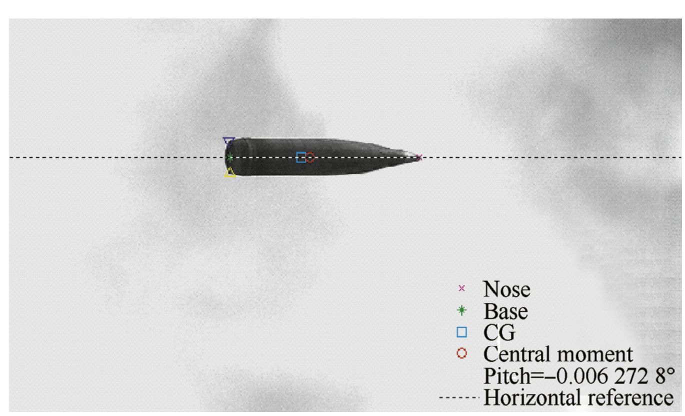

Fig. 2. Automated flight video analysis (AFVA) orientation measurement.