Study of Internal & External Ballistics for .177 cal & .22 cal Projectiles

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Abstract— This is a study of internal and external ballistics for .177 cal & .22 cal projectiles. Ballistics is a study of projectile in flight. Factors which affect the said ballistics situations have been discussed. The need of this study is to make the shooter more aware of the parameters, conditions, selection of rifle and projectiles, which affect the performance of the projectile fired.

Key words: Ballistics, Projectiles

I. INTRODUCTION

In the paper, internal and external ballistics have been discussed with their respective parameters. Twist rate of rifling, gyroscopic stability, design parameters of pellet have been discussed under internal ballistics. Projectile flight, gyroscopic effect, Magnus effect, cross wind effect, Corral's function and ballistics coefficient has been discussed under external ballistic.

Internal ballistics covers all aspects involving the ammunition and firearm from the moment the firing pin strikes the cartridge to the point at which the projectile exits the muzzle of the firearm. A range of scientific concepts underpin internal ballistics, which include combustion theory, Piobert's law of burning, the ideal gas law, laws of thermodynamics, conservation of energy and linear momentum, and Newton's laws of physics.

External ballistics covers the period of flight from the point at which the projectile is stable and behaving within 'normal' atmospheric conditions until the moment it comes into contact with an object. This section considers basic concepts that critically underpin this area of applied physics.

II. INTERNAL BALLISTICS

Internal ballistics starts with the ignition of the primer at the base of the rifle cartridge. This ignition causes the gunpowder inside the cartridge to rapidly burn, building up internal pressure. [1] As the internal pressure within the cartridge increases, the malleable brass cartridge case expands until it comes in contact with the chamber walls and the bolt face (in case of air pellet, the skirt of the pellet expands and seals the chamber). With the cartridge case tight against the chamber, the increasing gas pressure created by the burning powder finds the path of least resistance by forcing the bullet out of the cartridge case and down the barrel(in case of air pellet the high pressure air from the pre charged cylinder propels the pellet). [2] As the chamber pressure from the burning powder increases, this pressure accelerates the bullet to higher velocities. [3] Factors which influence internal ballistics are discussed below:-

A. The Twist Rate of the Barrel

The twist rate of the barrel determines the best bullet weight for the gun and is the single, most important factor for rifle accuracy .The manufacturer cuts the rifling to a twist rate that will stabilize the bullet designed and tested for that cartridge. [4] The smaller the bore diameter, the more difficult it is to stabilize a bullet. Heavy bullets cannot be driven to the same velocities as lighter bullets in the same barrel, so they are also not spinning as fast leaving the muzzle and may not stabilize down range. [5] Bullet spin is a product of twist rate and velocity. If a bullet is not spinning fast enough, a target will have oval or keyhole hits. Using a light bullet in a fast twist rate barrel may cause the bullet to skip across the rifling and literally file itself, resulting in larger groups. Matching the bullet weight to the twist rate and velocity is essential for accuracy. For a bullet to fly point-forward, it must spin fast enough to be stable. For stability, the "gyroscopic stability factor", this depends on the spin rate. The spin in flight declines considerably more slowly than the forward velocity, the bullet's stability factor increases as it flies downrange and it actually becomes more stable. [6] Consequently, the stability factor at the muzzle is the most significant. Since the spin rate at the muzzle depends on rifling twist, twist is an important part of the stability factor.

B. Bullet Parameters (similar for air rifle pellet):

Besides weight, there are five measurements that are considered when selecting a bullet. Sectional Density: A weight to length ratio measurement. The longer and heavier the bullet, the higher the sectional density thus the deeper it will penetrate. This parameter is not important for target and varmint loads but is very important for game hunting loads. Ballistic Coefficient (BC): [7] The higher the BC, the more aerodynamic the bullet, thus it will drop less at long ranges and will be less affected by cross winds. Due to air density, small diameter bullets such as a .224" typically have poor BCs. A 6mm bullets and larger start getting higher BCs. A BC of .400 is considered very good, .500 and higher is excellent. Bore Surface is the length of the bullet that actually touches the bore. The longer the bore surface, the more it dampens effects from bullet jump shock and the more stable the bullet will be going down the barrel. This parameter is very important for accuracy. [8] Ogive is the point on the nose where the bullet first measures full diameter. This important parameter will dictate bullet seating depth, bullet jump and cartridge overall length. All bullets must be seated at optimum depth for best accuracy. This usually occurs where the ogive is .010" from the rifled bore. [9]

C. Gyroscopic Stablity

A gyroscope is a spinning mass with the majority of its weight located about the circumference. Gyroscopes, once spinning, have a tendency to resist changes in orientation. If a gyroscope is tilted while spinning it precesses about the relative axis. The faster the gyroscope spins the more resistive force the gyro exerts. A bullet or air pellet rotates around its axis of travel and also precesses relative to the ground because of gravitational drop, which creates a it a gyroscope.

D. Longer Rifle Barrel

A longer rifle barrel has the advantages of a longer sight radius, theoretically allowing a shooter to obtain a higher degree of accuracy from the improved precision of the sights alone. [10] A longer barrel also provides a longer path for the projectile to stabilize prior to exiting the barrel, while allotting a longer period of time for the propellant charge to act on the projectile, often resulting in higher muzzle velocities and more consistent trajectories. A long barrel inherently provides more mass available for heat transfer, increasing the heat transfer rate incurred between shots, in turn allotting less warpage in the barrel, helping to improve consistency (and ultimately accuracy).It should also be noted, as the barrel length increases, the barrel's center of mass moves further from the geometric center in regards to the rifle itself and makes the rifle harder to support. In effect, a shorter barrel will tend to keep the centre of mass closer to the geometric center of the rifle, a desired effect, as longer barrels tend to produce muzzle heavy rifles, which negatively affect shooting conditions. [11]

III. EXTERNAL BALLISTICS

The study of external ballistics begins when the bullet leaves the muzzle of the rifle barrel and becomes a projectile traveling towards a target. There are three forces that influence a bullet's flight, Gravity, Air Resistance or Drag [12], and Wind. Gravity is a constant force that draws all objects toward the center of the earth(Fig-1). As soon as the bullet leaves the rifle muzzle it starts dropping toward the earth.

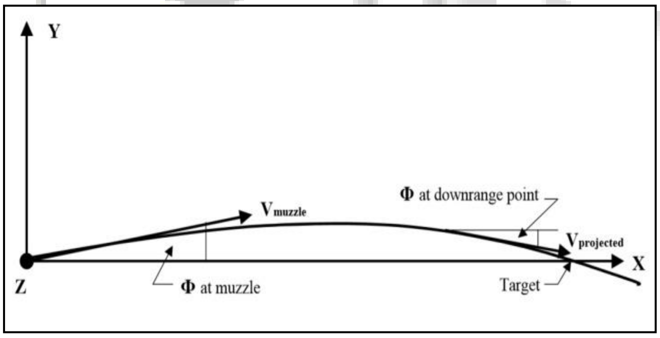

Fig. 1:

When marksmen speak of vertical drop, they're referring to the amount of drop, in inches, that the bullet experiences due to gravitational pull. So, the longer the time of flight of the bullet, the greater the amount of vertical drop, because gravity has more time to influence the bullet. [13] The velocity of a bullet can minimize the effects of gravity. The faster a bullet can travel the distance to a target, the less time that gravity can act upon it. Since gravitational pull is constant, ballistic charts can predict how much vertical drop a bullet will have, at a specific velocity and distance. Air resistance or drag is the force that slows the bullet down. The amount of drag that a specific bullet experiences varies depending on the bullet's velocity, shape, weight. As the bullet travels, it has to push air out of the way. This air is compressed in front of the bullet and then forced out of the way, sliding down the sides of the bullet. The movement of air down the sides of the bullet creates drag because of friction. [14] The air moves from the sides of the bullet to the bullet's rear. This causes a vacuum to form, slowing the bullet even more. The shape and design of a bullet can reduce this drag. Environmental factors of altitude, temperature, and humidity also create drag in that the more dense the air the bullet passes through the more drag it experiences Bullets are manufactured in a variety of shapes, sizes, calibers, and materials. [15] Some designs are more efficient at traveling through the air than others. The efficiency of a bullet is referred to as the Ballistic Coefficient (BC). The ballistic coefficient or BC is expressed as a three-digit number, which is always less than one. (e.g., .250, .530) The higher the number, the more efficient the bullet is in overcoming drag. A bullet's specific BC is found in ballistic charts. The higher the ballistic coefficient, the flatter the bullet trajectory. [16] External ballistics is better understood if a marksman is familiar with some basic terminology and physical principals of a bullet in flight. If a rifle barrel is held parallel to the surface of the earth and a bullet is then fired from it, the bullet will start to drop toward the surface of the earth immediately upon leaving the rifle barrel, because gravity is pulling it toward the earth surface. [17]

This is called the Vertical Drop. The horizontal line between the target and the rifle barrel is referred to as the Base of Trajectory. In order to overcome or compensate for this vertical drop, a skilled marksman will intentionally aim a specific distance above the target. The target is referred to as the Desired Point of Impact. Where the bullet actually hits is referred to as the Point of Impact. Using rifle data or the commercially available ballistic charts, [18] marksmen will know how much a bullet will drop at a variety of distances. The angle that is created between the base of trajectory and how far the rifle barrel is pointed above the desired point of impact is called the Angle of Departure. There are two other terms used in association with the rifle barrel and where it is pointed. [19] The Line of Elevation is a straight line running down the bore of the rifle and going off into infinity. The Line of Departure is a straight line running down the bore of the rifle at the specific moment the bullet is fired. An unimpeded rifle bullet will never rise above the line of departure [20].

A. Gyroscopic Effect

The bullet starts out with its spin axis aligned with its velocity vector. As the trajectory progresses, gravity accelerates the bullet down, introducing a component of velocity toward the ground. The bullet reacts like a spiraling football on a long pass, by 'weather-vamping' it's nose to follow the velocity vector, which is a nose-down torque. The axis of rotation is that the nose points slightly to the right as it 'traces' to follow the velocity vector. [21] This slight nose right flight results in a lateral drift known as 'gyroscopic drift'. Having a left or right twist will change the direction of gyroscopic drift. Bullets fired from right twist barrels drift to the right, and vise versa by the same amount.(Fig-2) Gyroscopic drift is an interaction of the bullets mass and aerodynamics with the atmosphere that it's flying in. Gyroscopic drift depends on the properties (density) of the atmosphere. [22]

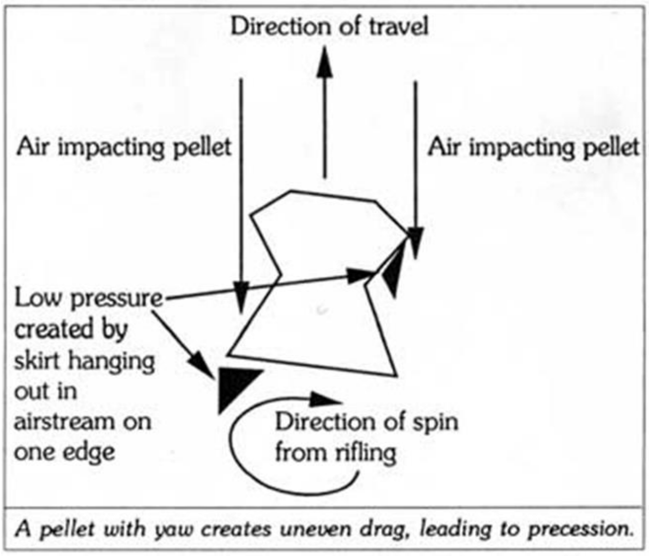

Fig. 2:

B. *Magnus Effect*

Magnus effect can be found is advanced external ballistics. A spinning bullet in flight is often subject to a sideways wind [23]. In the simple case of horizontal wind, depending on the direction of rotation, the Magnus effect causes an upward or downward force to act on the projectile, affecting its point of impact. Even in a complete calm, with no sideways wind movement at all, a real bullet will still experience a small sideways wind component. [24] This is due to the fact that real bullets have a yaw motion that causes the nose of the bullet to point in a slightly different direction that the bullet is actually travelling in. This means that the bullet is "skidding" sideways at any given moment, and thus experiences a small sideways wind component. The effect of the Magnus force on a bullet is not significant when compared to other forces like drag. (Fig-5) However, the Magnus effect has a significant role in bullet stability due to the fact that the Magnus force does not act upon the bullet's center of gravity, but the center of pressure. [25] This point is located either behind or in front of the center of gravity, depending on the flow field structure, in other words, depending on whether the bullet is in super-sonic or sub-sonic flight. The Magnus force thus affects stability because it tries to "twist" the bullet along its flight. Reverse Magnus effect is not discussed here.

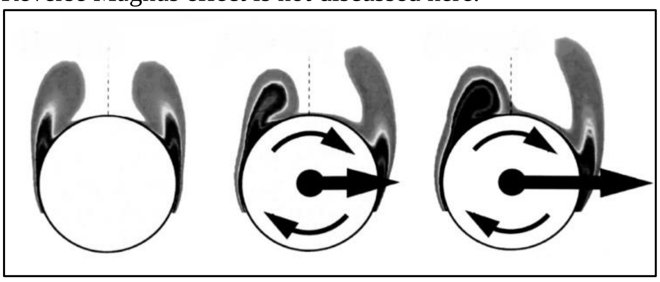

Fig. 5:

C. *Cross Wind Effect*

For a bullet with right hand spin for a cross wind blowing from the shooter's left (Fig-3). [26] The trajectory then curves to the shooter's right to follow the crosswind. As the trajectory curves the bullet gains a velocity relative to the ground in the cross angle direction.

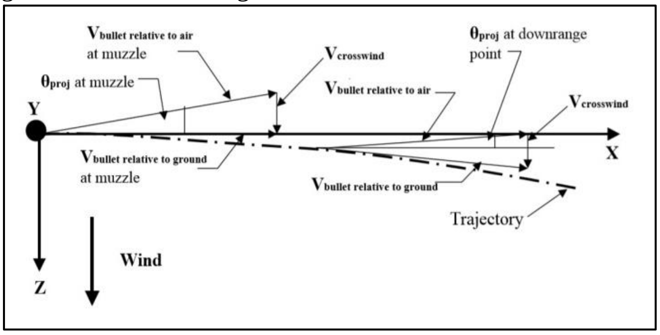

Fig. 3:

For a bullet with right hand spin for a cross wind blowing from the shooter's right.(Fig-4) The trajectory then curves to the shooter's right to follow the crosswind. As the trajectory curves the bullet gains a velocity relative to the ground in the cross angle direction.

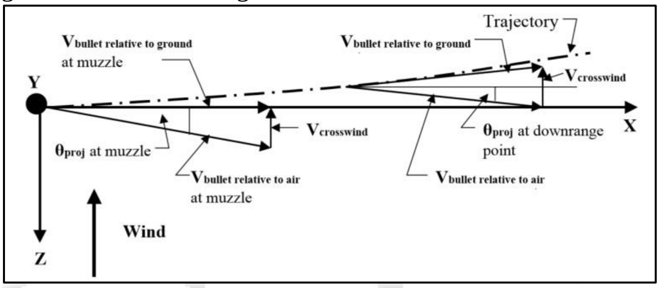

Fig. 4:

D. *Coriolis Acceleration*

Accelerations due to the Coriolis Effect are caused by the fact that the earth is spinning, and are dependant on position on planet and the direction of firing. There are horizontal and vertical components to Coriolis acceleration. The Horizontal component depends on latitude, which is how above or below the equator. Maximum horizontal effect is at the poles, zero at the equator. The horizontal component is independent of direction of shooting. Typical horizontal Coriolis drift for a small arms trajectory fired near 45 degrees North Latitude is about 2.5-3.0 inches to the right at 1000 yards. The Vertical component of the Coriolis effect depends on direction of shoot, as well as position on the planet. Firing due North or South results in zero vertical deflection, firing East causes to hit high, West causes to hit low. The vertical component is at a maximum at the equator, and goes to zero at the poles. Typical vertical deflection at 45 degrees North (or South) latitude for a 1000 yard trajectory is the same as for the horizontal component: +2.5 to 3.0 inches (shooting east), or -2.5 to 3.0 inches when shooting west. The effects of gyroscopic drift and Coriolis drift are independent, and cumulative.. For example (typical 1000 yard small arms trajectory), shooting in the northern hemisphere where the horizontal drift is always to the right, having a right twist barrel, then the bullet will drift to the right approximately 9" due to gyroscopic drift, and an additional 2.5" due to Coriolis, resulting in 11.5" right drift, even in zero crosswind. However, with a left twist barrel in the northern hemisphere, gyro drift and Coriolis drift would partially offset each other, resulting in only 6.5" drift to the right [27].

E. Muzzle Velocity and Kinetic Energy

During internal ballistics, approximately 30% of the energy created is actually transferred to the projectile(s), predominantly in the form of kinetic energy, resulting in acceleration of the projectile(s) to a known velocity. Following muzzle exit and a very short distance past the muzzle, the projectile reaches a maximum velocity, referred to as muzzle velocity. Muzzle velocity is pre-determined by the ammunition manufacturer; however, as previously explained, fired projectiles may not reach the technical specification of muzzle velocity quoted by the ammunition manufacturer. Kinetic energy and muzzle velocity are two of three linked factors; the third component that affects muzzle velocity and the kinetic energy is the projectile mass. As the mass of the projectile increases, a greater amount of work, force and energy is required to move the projectile. [28] Therefore, for two projectiles of different masses to have the same muzzle velocity, more kinetic energy (and therefore a higher gas pressure) is required to fire the heavier projectile. A projectile with higher mass will ultimately enhance its ‘carrying power’. When considering terminal ballistics later on, the kinetic energy of the projectile is of greater importance than the velocity of the projectile, as kinetic energy takes into account both projectile mass and velocity. It is also the ability of the projectile design to transfer energy to the other object that impacts on the resulting damage to the object. As soon as the projectile exits the muzzle, the energy and force acting on the projectile is in the forwards (horizontal) direction away from the muzzle, therefore the velocity vector has a positive value. Initially this will be the dominant direction of force acting on the projectile. [29]However, unless the projectile is fired into a vacuum, there will always be forces acting against the projectile in the opposite direction limiting the forwards progression, reducing the kinetic energy and therefore the velocity of the projectile over time. These opposing forces are from the interaction with molecules within the atmosphere; the phenomenon is known as air resistance (drag). The forward movement of the projectile compresses the air molecules in front of it causing areas of higher pressure which act in all directions around the front of the projectile. Minimizing the cross-sectional area of the projectile and making the projectile less angular will reduce air resistance. The air molecules then flow around the projectile, a small amount of surface (skin) friction is created between the air molecules and the sides of the projectile, further reducing the kinetic energy and velocity of the projectile. When the air molecules have passed over the sides of the projectile, they have to fill in the space left by the base of the projectile. This again causes high-pressure regions at the back edges of the projectile and leaves a turbulent wake of gas behind the projectile. The shape of the nose and base of the projectile are therefore critical to limiting the effect of air resistance on the kinetic energy and velocity of the projectile. A more aerodynamically shaped projectile will exhibit a slower decline in velocity and kinetic energy due to air resistance. Aerodynamically shaped projectiles will display a long, sharp and low-angled nose to reduce the cross-sectional surface area initially presented to the air and may even have a slightly angled base to improve the flow of air particles and reduce turbulence from air molecules behind the projectile. The term ballistic coefficient is used to calculate the decline in projectile velocity due to the air and takes into account projectile mass and diameter. [30] Typically, the higher the ballistic coefficient, the better a projectile retains its velocity over time.

IV. CONCLUSION

As the shooting distance in .22 cal events and .177 cal events are fixed selection for bullets and pellets should be done for maximum ballistic coefficient, with consideration of weight, propulsion medium and force exerted, rifling rates, barrel sealing property to utilize maximum air pressure in case of .177 cal air pellet.

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