Hyper-Stabilized Rifle Bullets

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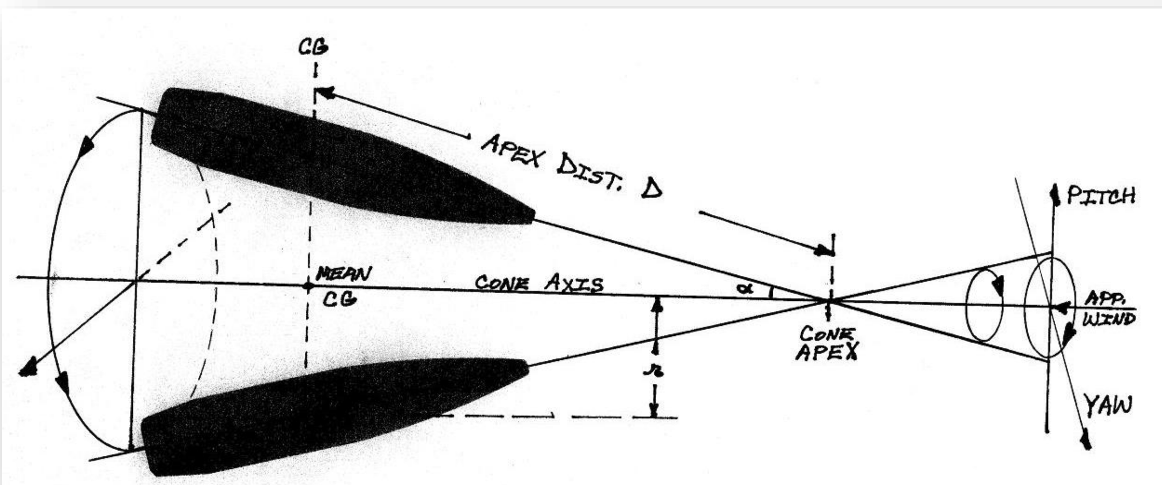
How Rifle Bullets Actually Fly

Correctly understanding how their fired bullets actually fly through the air can be advantageous for serious riflemen, especially those competing in Extreme Long-Range (ELR) matches. The obsolete idea that a rifle bullet flies through the air with its center of gravity (CG) nailed to a smooth trajectory while its nose spirals around pointing outward is simply incorrect. Any 6-degree-of-freedom (6-DoF) flight simulation shows that this cannot be the case. The CG of the bullet rotates about its mean trajectory 180 degrees out of phase with the gyroscopic precession of its spin-axis direction.

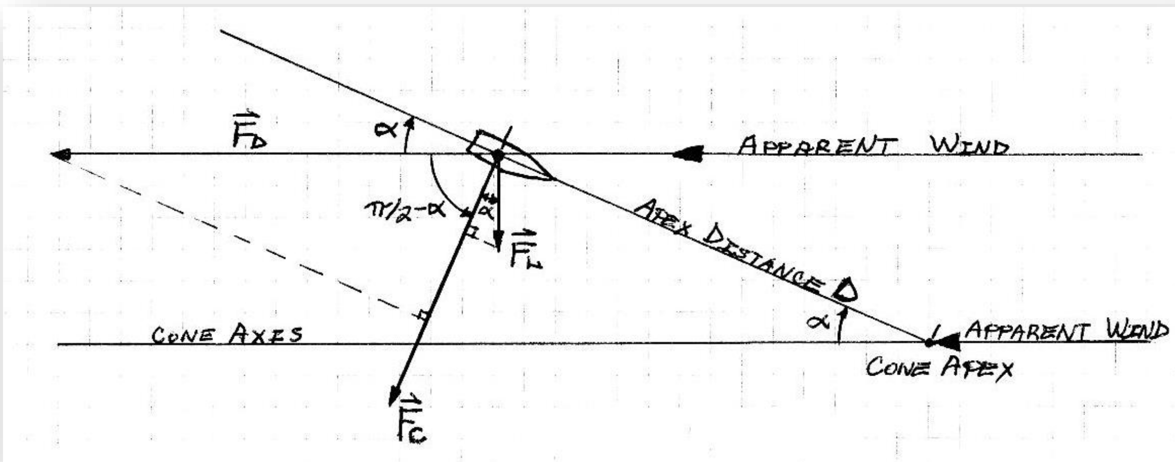
As a physicist, I developed what I call the *Coning Theory of Bullet Motions* from 6-DoF flight simulation data originally supplied by Bryan Litz about a decade ago. That coning motion obeys the rules of classical mechanics. I also have several PRODAS runs supplied by the Army for joint ballistic studies which also support my Coning Theory.



The above diagram illustrates the actual coning motion by showing the extreme upper and lower coning positions for a right-hand spinning bullet and its spin-axis pointing directions. As with any spin-stabilized projectile, a fired rifle bullet "cones" around its mean trajectory with its nose angled inward toward that trajectory.

The free-flying spin-stabilized rifle bullet acts as a gyroscope. An aerodynamic over-turning moment acting on the gyroscopically stabilized bullet causes its spin-axis to precess about the direction from which the airstream is approaching the bullet. The “slow-mode” precession rate of that gyroscopic motion establishes the coning rate of the flying bullet.

The CG of the coning bullet orbits around a “mean CG” location which moves smoothly along the “mean trajectory” at the “mean velocity” of that bullet. This orbital motion of the bullet’s CG is powered by the aerodynamic forces of lift FL and drag FD as shown in the diagram below.



Here the aerodynamic forces are shown acting on the bullet at its extreme upper position in a coning cycle. The resultant coning force vector F_C acting at right angles to the coning distance vector **D** and toward the coning axis actually powers the orbital coning motion of the CG of the bullet. The coning motion is a circular, torsional harmonic oscillation at the coning angle **α**. As with any harmonic oscillation, the coning rate and the coning amplitude (here the coning angle **α**) are independent of each other.

The axis of the coning motion changes direction very quickly when necessary to align itself directly into the approaching airstream seen by the moving bullet. That airstream is termed the “apparent wind” as experienced by the moving bullet. Each time the coning axis has to change direction to track any change in direction of this incoming apparent wind, the size of the coning angle **α** (temporarily) *increases* by that *same angular difference*.

The energy required to accomplish this shift in coning axis direction is extracted directly from the kinetic energy of the flying bullet in the form of increased aerodynamic drag. Only an *increase* in the coning angle **α** of the bullet can extract this needed amount of kinetic energy by increasing the yaw-drag experienced by that moving bullet. The coning angle only decreases with slow-mode frictional damping during subsequent flight for any dynamically stable rifle bullet.

Hyper-stable flight occurs when these continuing rates of increase and decrease of the coning angle *just offset* each other, and the flying bullet cones around with a very small "irreducible minimum" coning angle. The yaw-drag experienced by a bullet in subsequent hyper-stable flight is essentially zero because the bullet is flying essentially "nose forward" in that flight regime.

We have to introduce a few basic equations at this point because they are key to understanding hyper-stable flight. In linear aeroballistic theory, we accurately model the magnitude of the aerodynamic force of drag F_D in ballistic flight as

$$F_D = q*S*CD$$

$$CD = [CD_0 + (Sin^2\alpha)*CD\alpha]$$

q = Dynamic Pressure

S = Frontal Cross-Sectional Area of the Projectile

CD = Total Coefficient of Drag

CD_0 = Coefficient of Drag for "nose forward" flight

α = Aerodynamic Angle-of-Attack

CDα = Coefficient of Yaw-Drag.

Each of the two component drag coefficients, CD_0 and **CDα**, are dimensionless numerical values which depend heavily upon the airspeed of the projectile expressed as a Mach Number with Mach 1.0 being the "speed of sound" in ambient conditions. The aerodynamic force of drag F_D is solely responsible for retarding the forward motion of any projectile in ballistic flight. The product, **q*S**, is a type of maximum "potential" drag force which would be experienced by a very "non-streamlined" projectile.

Bullet designers strive to minimize the drag curve CD_0, as a function of Mach-speed, often at the expense of some increase in the yaw-drag curve **CDα**, which is also a function of Mach-speed. Bullet designers can decrease the zero-yaw coefficients of drag CD_0 of our bullets, but it is then up to the rifleman to ensure his bullets fly exactly nose-forward.

For example, if $CD_0 = 0.320$ for some projectile at some Mach-speed, and **CDα = 4.4** at that same airspeed, the total coefficient of drag **CD** for an angle-of-attack **α** of **5.7 degrees** would be **0.364**, for a **13.75-percent** increase due to yaw-drag at this feasible coning angle-of-attack. [These are actual drag coefficient values per Bob McCoy for the old 30-caliber 168-grain Sierra International bullet at an airspeed of **Mach 2.5**.]

These values are shown to illustrate the relative importance of yaw-drag in rifle ballistics. While CD_0 would be much smaller for a modern ULD bullet at this airspeed, its yaw-drag coefficient **CDα** will likely be much larger due to the extra nose-length of that newer design ULD bullet.

Definition of Hyper-Stability

A hyper-stabilized rifle bullet flies with insignificantly small angular amplitude **α** of its coning motion throughout its flight. The minimum possible coning angle **α** in flat firing is the small change in the flight path angle of the trajectory due to gravity during each coning cycle as the coning axis tracks the downward arcing of the trajectory. The apparent wind seen by the coning bullet approaches from beneath its coning-axis direction by this small angular increment during each coning cycle.

"Flat firing" is usually defined by ballisticians as firing with a muzzle elevation angle of no more than 100 milliradians (5.7 degrees) above the horizontal. Even in horizontal ELR shooting, the muzzle elevation angle seldom exceeds 20 or 30 mils. We are not addressing uphill or downhill firing here.

In hyper-stable flight, the aerodynamic frictional damping of the coning angle **α** matches the incremental increase in that coning angle **α** during each coning cycle which is caused by the downward curvature of the trajectory. The initial coning rate of a spin-stabilized rifle bullet is typically 40 to 70 cycles per second and decreases very slowly over even an extended time-of-flight.

The total change in flight path angle from muzzle to target is usually about 2 to 4 times the muzzle elevation angle (above the horizontal) required to hit any particular target at distances at least to "maximum supersonic range." For a high-velocity rifle bullet fired more or less horizontally, the flight path angle changes downward by less than 0.10 degrees during each coning cycle throughout its entire supersonic flight.

I restrict my comments here to "supersonic flight" simply because I have not yet had the opportunity to study adequately the transonic and subsonic flight of rifle bullets optimized for lowest supersonic zero-yaw drag. One might hope that a hyper-stable ULD rifle bullet will punch through the turbulent transonic airspeed region and continue on in stable flight as a reasonably good subsonic projectile.

The hyper-stable bullet flies with a "steady-state" coning angle **α** smaller than 0.10-degree size. This small coning angle **α** is also its long-term aerodynamic angle-of-attack **α**. Thus, for aerodynamic yaw-drag calculation purposes, the coning rifle bullet is flying essentially "nose-forward" (with $\mathbf{Sin^2\alpha < 0.000003}$) in this hyper-stabilized flight mode.

Why is Hyper-Stability Important?

Any hyper-stable rifle bullet is flying with its particular minimum possible retardation, the "nose forward" aerodynamic drag coefficient **CD_0**, with no added contribution of yaw-drag **$CD\alpha$**. More of its original speed and kinetic energy are carried further downrange. The "maximum supersonic range" of that hyper-stable bullet is significantly extended.

Of special importance to competition shooters, the crosswind sensitivity of a hyper-stable rifle bullet is significantly reduced. Accurate Ballistic Coefficient (**BC**) measurements made by firing hyper-stabilized rifle bullets will consistently be **10 to 20 percent higher** than similar measurements made when those same bullets were fired with only marginal initial gyroscopic stability (**Sg = 1.4**).

In fact, it was a screen-shot from David Tubb's Oehler System 88 on his 1000-yard range that first led me to investigate the cause of an unexpectedly high **BC(G1)** measurement. His System 88 reported a 5-shot average **BC(G1)** of **0.794** (for an ASM atmosphere) at an average airspeed of **Mach 2.46** for a 225-grain 338-caliber test version of my own new Monolithic copper ULD bullet design. Bob McCoy's similarity-based McDRAG program estimated a **BC(G1)** of only **0.703** (for an ICAO atmosphere) for these test bullets at **Mach 2.5**.

Only 0.5 percent of this difference is attributable to the different densities of the two standard atmospheres. The 5 individual shot measurements were adequately self-consistent, so that experimental error cannot likely explain the remaining 12.4 percent difference. David said that the Schneider P5 rifling pattern of his test barrel and a 21 MPH tailwind might account for perhaps 20 to 30 points of this **BC(G1)** measurement. Checks with Ken Oehler assured me that his System 88 software calculations had indeed properly accounted for the 21 MPH range wind during the firing test.

The test bullets supplied to David had been base-drilled in manufacturing for at least marginally stable flight from existing 10-inch twist 338 rifle barrels. David's 338 Lapua Magnum test barrel was a new 35-inch Schneider barrel with P5 rifling at **7.5 inches per turn**, no doubt intended for firing other more-difficult-to-stabilize monolithic ULD bullets. The initial gyroscopic stability **Sg** of these base-drilled test bullets which David fired at an average muzzle speed of 3378 feet/second has been reliably estimated to have been **2.75**. The average time-of-flight to 995.7 yards was acoustically measured at 1.068 seconds, with an average calculated arrival speed of 2325 feet/second (Mach 2.1).

I suspect that in developing his similarity-based McDRAG program for projectiles using ogive head-shapes, McCoy was inadvertently predicting the total coefficients of drag **CD**'s for projectiles flying with significant, but unmeasured, coning angles because of the measurements data-set to which he was fitting his McDRAG calculations using multi-variate linear regressions. Incidentally, bullet design tools based on Computational Fluid

Dynamics (CFD) might well suffer this same flaw if their drag predictions are "normalized" in any way against test-firing data.

In attempting to understand this anomalous **12.9 percent** higher **BC(G1)** measurement, I was eventually able to use Coning Theory to develop the concept of ***hyper-stable*** bullet flight. Without these fortuitous circumstances, we might never have tested our bullets with an initial **Sg** as high as **2.75**.

How is Hyper-Stability Achieved?

Conventional jacketed, lead-cored rifle bullets are fired with minimum or marginal initial gyroscopic stability **Sg** from slow-twist-rate rifle barrels. Riflemen seeking minimum impact dispersion across their targets have long since developed this strategy of using the slowest possible rifling twist-rates in their match barrels. The impact dispersions which they seek to minimize are "lateral throw-off" errors due to firing bullets which are statically imbalanced as manufactured, and which often suffer significant in-bore yaw during firing.

The size in inches of the lateral throw-off miss-distance across the face of the target equals the product of 1) the individual CG offset-distance in inches from the axis of the barrel, 2) the initial spin-rate of the fired bullet in radians per second, and 3) the time-of-flight to the target in seconds. In-bore yaw also typically offsets the CG of the bullet away from the axis of the bore, usually in the radial direction of the nose offset. [The reader is referred to the excellent discussion of the static imbalance of jacketed, lead-cored rifle bullets in Chapter 5 of *Modern Advancements in Long Range Shooting*, Volume I, (2014) by Bryan Litz.]

For aeroballistic reasons, the size of the first maximum yaw angle in ballistic flight is typically about 20 times the angular size of whatever in-bore yaw occurred within the rifle barrel, usually just as the bullet was being engraved by the rifling. This first maximum yaw angle becomes part of the initial coning angle $\boldsymbol{\alpha_0}$ as the bullet commences ballistic flight.

As shown in numerous 6-DoF simulation runs, a marginally stabilized rifle bullet (**Sg ≈ 1.4**) typically flies with a coning angle $\boldsymbol{\alpha}$ of about 2 to 5 degrees during much of its supersonic flight to the target. The coning angle of the spin-stabilized rifle bullet is also its aerodynamic angle-of-attack.

The total aerodynamic drag coefficient **CD**, which we often measure for rifle bullets in outdoor firing tests, includes a significant amount of "yaw-drag" due to flying with a significant aerodynamic coning angle-of-attack $\boldsymbol{\alpha}$ during all or much of its flight. This coning angle $\boldsymbol{\alpha}$ is never measured and reported in these firing tests because of the difficulty and expense of doing so. Disputes about the true Ballistic Coefficients (**BC**'s) of particular bullets have arisen due to this unmeasured variance in yaw-drag.

By instead selecting CNC-turned monolithic copper-alloy bullets, riflemen are freed from any concern about the static imbalance of their bullets. By ensuring that their rifle bullets are well aligned with the axis of the rifle barrel during firing, the concern about in-bore yaw causing a CG offset during firing can also be minimized. Except for rifling engravement, these monolithic copper-alloy bullets do not permanently deform in the rifle barrel during firing.

Monolithic copper-alloy bullets can also withstand at least twice the initial spin-rate of comparable jacketed, lead-core rifle bullets without danger of core-stripping or disintegrating in flight. Well-aligned monolithic copper-alloy rifle bullets can be fired with greater accuracy from rifle barrels made with much faster twist-rates than have been used traditionally.

By selecting rifle barrels made with twist-rates of approximately **20 calibers per turn**, even the current generation of very slightly long-for-caliber CNC-turned copper-alloy bullets can achieve hyper-stable flight very quickly out of the muzzle of the barrel.

In comparison, many current match rifle barrels are made with slow twist-rates of 39 to 46 calibers per turn. Here, we term the minor inside, or "bore," diameter of the rifled barrel as "1.0 calibers." Rifle bullets are usually sized by "groove" diameter of the barrel instead. As a point of reference, artillery tubes are often rifled at 20 to 25 calibers per turn.

If you initially spin your monolithic copper-alloy bullet a little faster than necessary, no harm is done, but you are not gaining anything either. If you initially spin them a little too slowly, your bullet will fly with some extra yaw-drag for the first several coning cycles, covering perhaps 40 to 100 yards of flight distance, before settling into hyper-stable flight for the remaining distance to the target.

When fired at high speed from barrels rifled at **20 calibers per turn**, current monolithic ULD bullets should have initial gyroscopic stabilities **Sg** of **2.5** to **3.0** in any firing conditions. For a "338-caliber" rifle bullet fired from a barrel having a 0.330-inch bore, **20 calibers per turn** would require the barrel to be made with a twist-rate of **6.60 inches per turn**. A 30-caliber barrel would need a **6.00-inch** twist-rate for hyper-stabilizing its bullets, etc.

These slightly longer-nosed monolithic copper-alloy bullets are designed to fly with much lower zero-yaw coefficients of aerodynamic drag (**CD_0**) at all supersonic airspeeds. We term these new bullet designs "Ultra-Low-Drag" or ULD bullets. Many well designed CNC-turned monolithic ULD bullets are already available, with new designs arriving frequently.

In fact, I am currently wrapping up development testing of my own new monolithic ULD bullet design, as mentioned earlier. It is both ultra-low-drag and self-aligning in the barrel during firing. That new bullet design is protected under US Patent No. 9,857,155 B2 issued January 2, 2018. The prototype test bullets are being made by Dan Warner of Warner Tool Company in New Hampshire.

Being significantly lighter in weight than a similar-length traditional lead-cored match bullet in each rifle caliber, any monolithic copper-alloy ULD bullet can also be fired safely at much higher muzzle velocity from any given cartridge.

By achieving hyper-stable flight right out of the muzzle, a rifle bullet can fly all the way to its distant target with its lowest possible aerodynamic drag (**CD_0**). In general, hyper-stable flight is achieved earlier in flight by firing bullets with an initial gyroscopic stability **Sg** of at least **2.5**, by launching these bullets perfectly with no initial yaw or yaw rate, by firing at higher muzzle speeds, by firing in light, steady crosswinds, and by firing through a lower-density atmosphere.

On the other hand, if modern monolithic ULD bullets are fired from conventional twist-rate rifle barrels with minimum or marginal initial gyroscopic stability (**Sg = 1.4** or **1.5**), the BC's of these ULD bullets measured in firing tests will likely be ***lower*** than that of some of today's heavier jacketed, lead-cored match bullets.

By lengthening the nose of his ULD bullet design to minimize its zero-yaw coefficient of aerodynamic drag **CD_0**, the bullet designer has also unintendedly increased the yaw-drag coefficient **$CD\alpha$** of his new ULD bullet. These new monolithic ULD bullets really must be spun a lot faster out of the muzzle to achieve their intended performance.

In summary, if a rifleman is serious enough to purchase expensive CNC-turned monolithic copper-alloy ULD rifle bullets specially for use in ELR shooting, then he should fire them from a rifle barrel having approximately a **20-caliber** twist-rate to enjoy the full advantages of hyper-stabilizing those bullets early in their flights. I am certain of these advantages in flat firing to maximum supersonic range. Beyond that, please let me know what you discover. I prefer to communicate by email: bcgi@centurytel.net .

Interior Ballistic Effects of Fast-Twist Rifle Barrel

A 338 bullet fired at 3300 feet/second from a 6.6-inch twist-rate (20 calibers per turn) rifle barrel will be initially spinning at 6000 revolutions per second. The energy required to spin-up a 250-grain 338-caliber bullet to this spin-rate is 62.6 foot-pounds. The muzzle energy of this 250-grain bullet at 3300 feet/second is 6044 foot-pounds. The spin-energy is 1.04 percent of that kinetic energy produced.

If this bullet were only spun half as fast (3000 revolutions/second), the spin-energy would be one quarter as much, or 15.7 foot-pounds. In comparison, bore friction losses are nominally estimated at about 2 percent of the muzzle energy.

Rifling engravement forces are already significantly higher because of firing a monolithic copper-alloy bullet instead of a much softer jacketed bullet. "Shot start" pressure may be even slightly higher still because of the steeper rifling pitch-angle of the fast-twist barrel. The helix angle of the rifling at 20 calibers per turn is 360/20 = 18 degrees.

The amount of copper-alloy bullet material displaced during rifling engravement is 3.85 percent greater than with a similarly rifled slow-twist barrel with a 9-degree helix angle. This value relates to the work done during rifling engravement and not directly to the engraving force required.

Normal load development procedures should handle these differences routinely. That being said, any change in the rifle/cartridge/bullet system requires careful re-development of new loading data. This radical change in barrel twist rate might well affect the optimum propellant choices in some large, “overbore” cartridges, tending to favoring slower burn-rate powders. Propellant combustion is a “bootstrap” process which can be very sensitive to even minor changes in pressure and temperature during firing.

Can the Twist-Rate be Too Fast?

There are no further aerodynamic drag reductions below $\mathbf{CD_0}$ to be gained by spinning your selected rifle bullet any faster than required for it to achieve hyper-stability just out of the muzzle. Bullet designers are sure to “go crazy” in lengthening the noses of future monolithic copper-alloy bullet designs in effort to claim ever lower zero-yaw coefficients of drag $\mathbf{CD_0}$, pushing the required rifling twist-rates even faster. We will eventually reach a point of diminishing returns.

The hyper-stabilized rifle bullet might “fail to trail” (in artillery terms) and impact nose-high when fired for “maximum extreme range” at muzzle elevation angles greater than 30 degrees above the horizontal.

As the hyper-stabilized bullet reaches its high-altitude flight apogee, the reduced atmospheric density encountered there might perhaps cause that bullet to become technically “over-stabilized” and remain in a “nose-high” attitude during its low-airspeed descent. I doubt that this will happen, but the hyper-stable flight of rifle bullets is a new concept. We still have much remaining to investigate.