Gun Barrel Considerations

By Jeff Siewert

When it comes to barrel design for a given caliber, the first item to be considered is the barrel exit twist. The current “convention” is to specify the twist in “inches per revolution” or “mm per revolution”, but that doesn’t give a particularly good indication if the twist is fast or slow for the bore diameter. A much better metric for comparing barrel twist is “calibers per revolution”. Table 1 shows a list of barrel exit twists stated as “calibers per revolution” as a function of bore diameter and twist in inches per revolution. The red horizontal lines divide above and below 40 calibers per revolution twist rates; what could be considered the “somewhat fast” threshold. For reference, most large caliber artillery pieces have a twist rate of 20 calibers/rev.

Land Dia., in. >	0.219	0.237	0.250	0.256	0.270	0.277	0.300
Groove Dia., in. >	0.224	0.243	0.257	0.264	0.277	0.284	0.308
Twist, in/rev	**Twist: Calibers/Rev**						
12	54.8	50.6	48.0	46.9	44.4	43.3	40.0
11	50.2	46.4	44.0	43.0	40.7	39.7	36.7
10	45.7	42.2	40.0	39.1	37.0	36.1	**33.3**
9	41.1	38.0	36.0	35.2	**33.3**	**32.5**	**30.0**
8	36.5	**33.8**	**32.0**	**31.3**	**29.6**	**28.9**	**26.7**
7	**32.0**	**29.5**	**28.0**	**27.3**	**25.9**	**25.3**	**23.3**

Table 1: Caliber Per Rev Exit Twist vs. Bore Diameter

The current “winner” for fastest twist rate for SAAMI specifications is the 300 Blackout with 26.66 calibers per revolution twist rate. The fast exit twist rate is used to increase the gyroscopic stability (and affects the dynamic stability) of the projectile when fired in the subsonic or transonic flight regimes, but fast twists also contribute to large dispersion by increasing the angular rate and/or cross velocity of the projectile at muzzle release, assuming a fixed projectile in-bore tilt with respect to the bore axis. The 6.5mm Creedmoor and 6.5 PRC have exit twist rates of 31.25 calibers per revolution and are considered by many to be “fast” twist. As previously mentioned, for many artillery applications, a twist of 20 calibers per revolution is used.

Barrel exit twist is a key driving factor in determining the gyroscopic stability of a projectile. The gyroscopic stability of a projectile is given by Equation 1.

$$S_{go} = \frac{(2)(I_x^2)(p^2)}{(\pi)(\rho_o)(I_y)(C_{m\alpha})(d^3)(V_m^2)}:$$

Equation 1: Gyroscopic Stability Equation

Where:

S_{go} = Gyroscopic Stability Factor at the Muzzle
I_x = Projectile Polar Moment of Inertia
p = Projectile Spin Rate, radians per second
ρ_0 = Air Density at Gun Muzzle
I_y = Projectile Transverse Moment of Inertia
$C_{m\alpha}$ = Projectile Pitching Moment Coefficient Derivative
d = Projectile Reference Diameter
V_m = Muzzle Velocity

For a bullet to be gyroscopically stable, the gyroscopic stability factor must be greater than 1.0. It **is** possible to launch a projectile with a gyro stability factor slightly less than 1.0 and "get away with it" if the launch is nearly perfect, (as it is in most shoulder or hand fired small caliber weapons) because the bullet typically doesn't have to travel very far before the velocity has decreased to the point where the bullet is gyroscopically stable. Bullet designers, gun makers, and shooters who do this on a regular basis may get away with it for a brief time, but eventually the laws of physics catch up with them and in some situations, things can come unraveled rather quickly. Other methods of estimating gyroscopic stability, such as the Greenhill or Miller formulas, are outdated because of two primary factors:

- Neither consider the mass distribution within the projectile (e.g. moments of inertia) when assessing gyroscopic stability. As Equation 1 clearly shows, they are key parameters in determining stability.
- Neither formula considers the effect the projectile exterior shape has on the Normal Force Center of Pressure location (a key part of the $C_{m\alpha}$, pitching moment coefficient derivative factor in Equation 1) and its movement with projectile flight Mach number.

The discussion starting paragraphs use the term "exit twist rate" because barrels do not have to be made with constant twist rifling. The vast majority of small caliber guns use barrels have a constant twist rifling form, but that is done primarily to reduce the cost of manufacturing the barrel.

Constant twist barrels have performance drawbacks that have caused some small caliber barrel makers to consider other twist versus travel options for specific applications. Smith and Wesson recently introduced the XVR 460 revolver with a gain twist barrel to help ensure the bullet attains full spin without distortion in a high-performance handgun. Any time the bullet has appreciable "free run" prior to encountering the rifling, such as occurs in a revolver as the bullet makes the jump from the cylinder to the barrel, a gain twist rifling form can be used to reduce the magnitude of the "torque spike" that occurs when the bullet contacts the rifling at a velocity that's not close to zero. In the case of revolvers, the bullet might have to travel 0.2-0.5 inches or more between the time it's free from the case until it encounters the forcing cone of the rifling. Projectile velocity might be 200 – 500 feet per second depending on diameter and mass of the bullet and the pressure developed behind the projectile.

Gain twist barrels have an initial rifling angle that is typically something less than the exit twist, where the rifling angle starts (angle-wise) depends in large measure on application of the gun and the magnitude of the long-term expected free run to the rifling. Figure 1 shows the categories of twist vs. travel options available to the gun designer; the exit twist is shown at 10 deg. for this particular graph and the in-bore travel is "normalized" to 100 calibers.

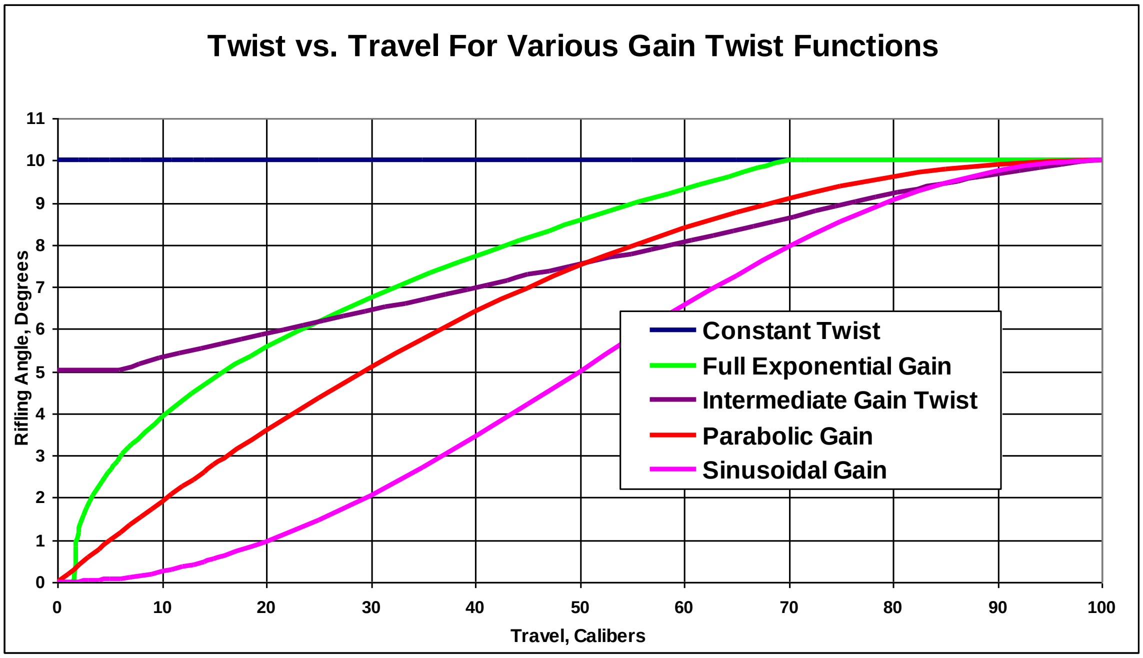

Figure 1: Barrel Rifling Twist Options

There are three full gain twist options shown in Figure 1, the full exponential gain twist, the parabolic gain twist, and the sinusoidal gain twist. These rifling profiles are referred to as full gain twist options because their initial rifling angle is zero. Of the full gain twist options, the exponential gain twist option is easiest on the surfaces of the projectile driving the projectile in rotation as the torque is put in earliest in the in-bore travel, while these contact surfaces are cold. The parabolic is next in line when considering band wear, and the sinusoidal gain twist comes in last because it attempts to put the torque into the projectile when its contact surface with the barrel is already hot from work already put into the bearing surface from projectile passage down the bore.

With any small caliber barrel employing gain twist rifling, care must be taken in designing the land and groove profile so the rifling angle change doesn't generate large circumferential loads at the forward bourrelet of the projectile and split the (occasionally thin) jacket wall.

Full gain twist rifling is advantageous for weapons where there is a reasonable expectation of an appreciable (>100 FPS) projectile velocity when the projectile encounters the forcing cone of the barrel, combined with a medium or large caliber projectile. In these situations, a non-zero twist angle may strip the material from the projectile intended to mate with the rifling in the barrel and thus fail to impart adequate spin to the projectile to provide gyroscopic stability. By making the initial rifling angle zero, the torque can be applied to the projectile gradually after it makes the jump to the rifling, reducing the peak load on the driving surfaces of the projectile, but also increasing the wear experienced by the projectile during in-bore travel.

Figure 2 shows the torque spike that happens in a constant twist barrel and a gain twist barrel when the origin of rifling is worn, or when firing in a revolver, and the projectile has some “free run” prior to encountering the rifling. For the constant twist barrel, the torque value is off the chart and very narrow, indicating the driving surface might be expected to strip due to the mechanical overload from hitting the rifling at an appreciable velocity.

If we look at the torque for the same projectile fired in a worn gain twist barrel, we see a smaller peak, which the driving surface (e.g. the projectile jacket) can withstand without stripping.

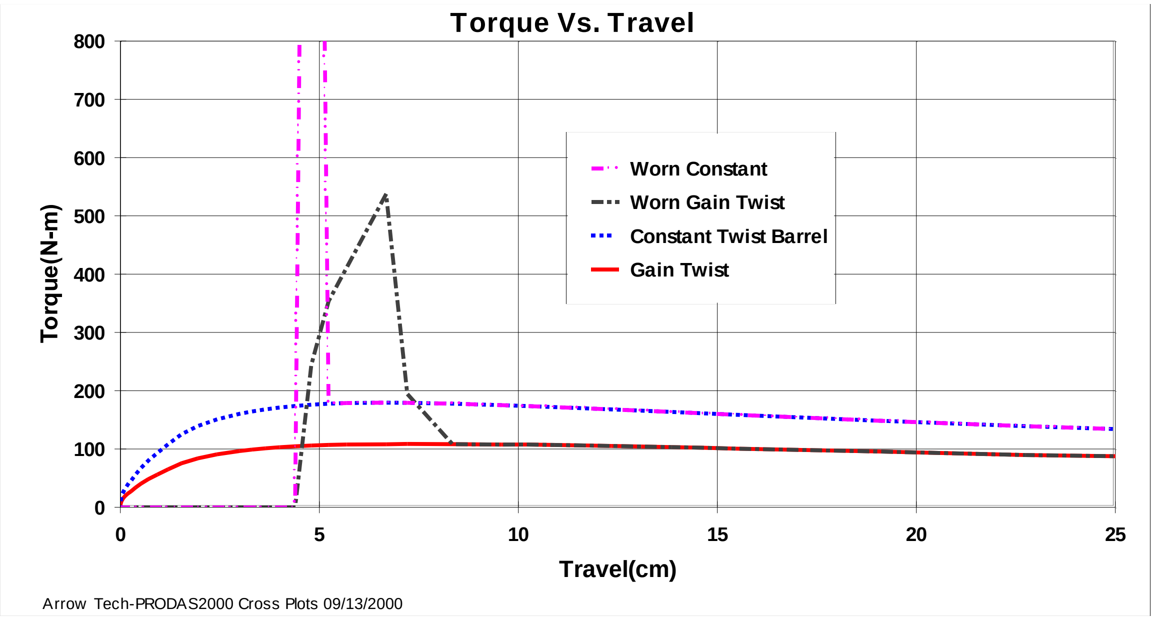

Figure 2: Torque vs. Travel For New and Worn Constant Twist and Gain Twist Barrels.

There are a couple of other basic parameters that define rifling form. They are:

1. Number of lands and grooves
2. Groove-to-land width ratio
3. Land profile shape (e.g. “standard” or polygonal)
4. Forcing Cone Angle

Each of these parameters is discussed in modest detail below.

Number of Lands and Grooves

The number of lands and grooves in the barrel primarily affects the number of raised surfaces in the barrel which cause the bullet to rotate as it travels down the barrel. To the best of my knowledge, barrels have been made with 2, 4, 5, 6, 7 and 8 lands and grooves in small caliber (50 cal and under). Generally, unless lead or other low melting temperature metals are used for the bullet interface with the rifling, there is little practical difference among the available choices for number of lands and grooves. Low melt temperature metals are adversely affected by lower numbers of lands and grooves as this increases the stress between the bullet and the land, leading to localized melting and deposition of bullet material in the bore. The higher the number of lands and grooves, the lower the peak bearing stress on the projectile and barrel, and the lower the wear on the driving surfaces acting to spin the projectile while it's in-bore.

Groove-to-Land Width Ratio

The groove-to-land width ratio is the dimensional width of the groove to the width of the land. The larger this ratio, the smaller the land is relative to the groove. Since all projectiles are tipped in-bore relative to the bore centerline, the wider the land (e.g. the smaller the groove-to-land width ratio) the more support the projectile has and the smaller the in-bore angle the projectile will attain in-bore for an equivalent clearance. Figure 3 shows the land width and groove width for a typical small caliber barrel. Looking at rifle barrels currently being produced or legacy systems already afield, the barrel with the narrowest lands is the 300 Blackout. Since the smallest diameter feature in the barrel (e.g. the land tops) controls the in-bore angle of the projectile relative to the bore centerline, having lands that are narrow is not conducive to keeping the in-bore angles small. This, combined with the fast twist of the 300 Blackout, may explain why dispersion is such a problem with some 300 Blackout ammunition types. Figure 3 shows the lands and grooves on a barrel cross section.

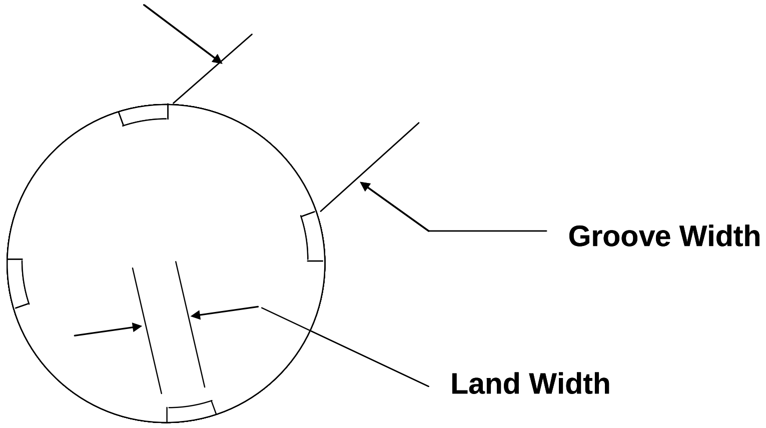

Figure 3: **Barrel Groove and Land Width**

Land Profile

The land profile affects the bore area of the barrel, the stresses applied to the projectile as it rotationally accelerates, and the dispersion observed for small caliber systems. Figure 4 shows a comparison of standard rifling geometry and polygonal rifling.

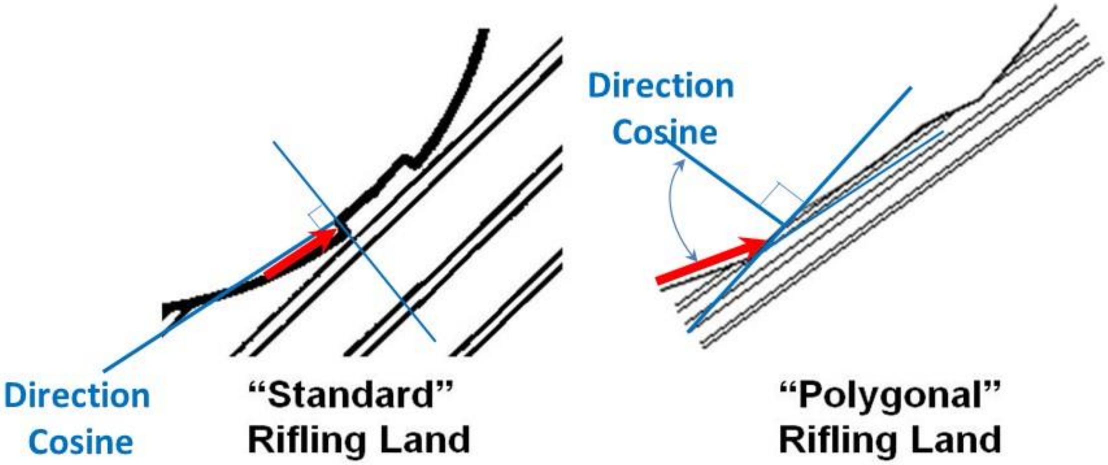

Figure 4: Comparison of Standard and Polygonal Rifling Cross Sections

The contact stress generated by rotational acceleration of the bullet stays constant with increases in the direction cosine of the land driving surface, but a considerable shear stress develops relative parallel to the land face, increasing the total stress on the contact surface between the land driving surface and the engraved surface on the projectile jacket. The relationship between land-jacket contact stress and driving surface sidewall angle is shown in Figure 5.

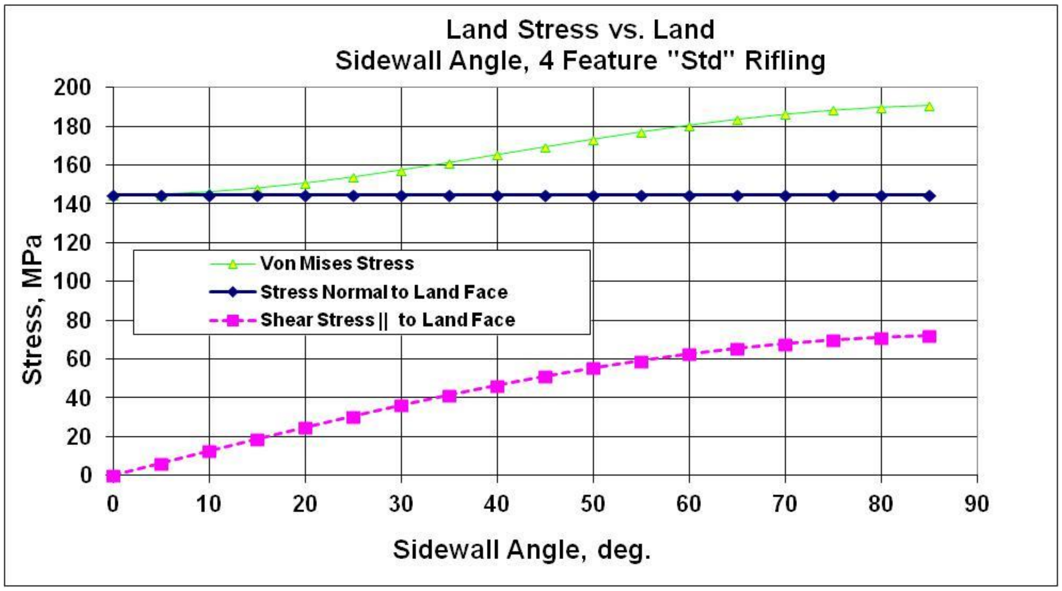

Figure 5: Peak Land Stress vs. Land Sidewall Angle, 4 Land & Groove Barrel

There does appear to be a distinct difference in dispersion (group size) performance between barrels with standard lands versus polygonal lands. Figure 6 shows the relative group size for different twist barrels (both cal/rev and in/rev are shown), for both standard and polygonal land geometry. The "mean" data represents the performance of about 195 shots spread over 3 rifles, using one lot of ammunition. The data is "normalized" to the baseline system, a 40 cal/rev barrel shooting a “match” bullet at a fairly modest range, at distance at which muzzle velocity variability and drag variability doesn’t greatly affect the group size.

The 1 in 12-inch twist barrel with standard rifling geometry is shown on the right-hand side of Figure 6 as the purple vertical line at 40 cal/rev. Also shown in Figure 6 is the one turn in 10 inch twist barrels (the yellow vertical line) near the middle of the figure, and the one turn in 8 inch twist barrels, shown as the light blue vertical line on the left hand side.

The average dispersion of the dispersion in the standard land geometry barrels is plotted as the solid red (nearly) horizontal line, and the dispersion of the projectile fired in barrels with polygonal rifling is shown in the solid green horizontal line. The black line, slashing diagonally downward from left to right is the average dispersion that would be expected from the standard projectile if the dispersion at this performance level were driven solely by characteristics that are sensitive to exit spin, namely center of gravity offset, principal axis tilt, and/or in-bore clearances. Since the average dispersion does not follow the black line until we get to twist rates under 1/10”, it can be concluded that the primary causative of dispersion at this performance level is not primarily driven by factors sensitive to barrel exit twist. Interestingly, the mean plus one standard deviation for the standard land geometry barrel **DOES** nearly parallel the light green line between 33.33 cal/rev and 26.66 cal/rev. This means that “fliers” away from the average dispersion ARE sensitive to exit spin rate, and hence barrel twist rate, at least for those bullets fired in barrels with standard rifling.

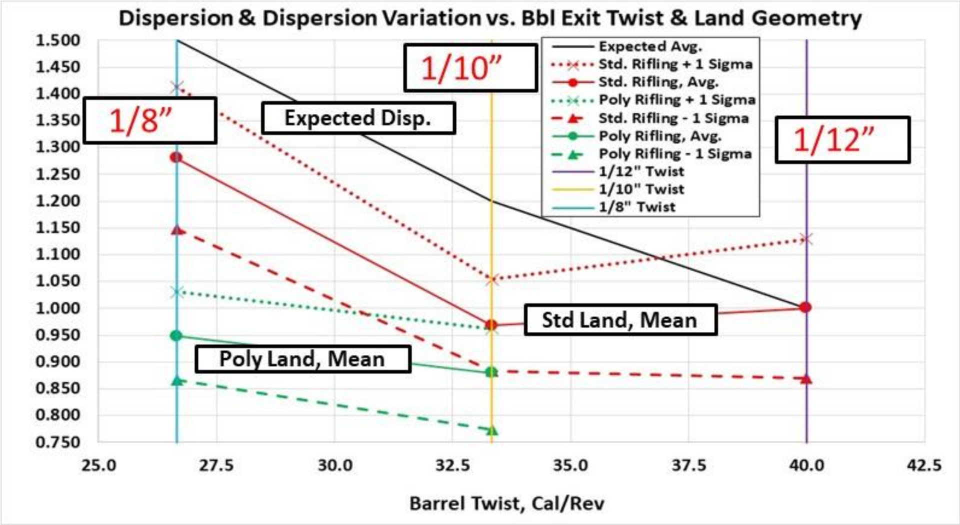

Figure 6: Relative Observed Group Size vs. Barrel Twist and Land Geometry

Forcing Cone Angle

Another factor sure to influence dispersion at longer ranges in an indirect manner is the effect of forcing cone angle on average engraving pressure and engraving pressure variation. Figure 7 shows the effect of changing the forcing cone angle on the average engraving pressure and the engraving pressure variation.

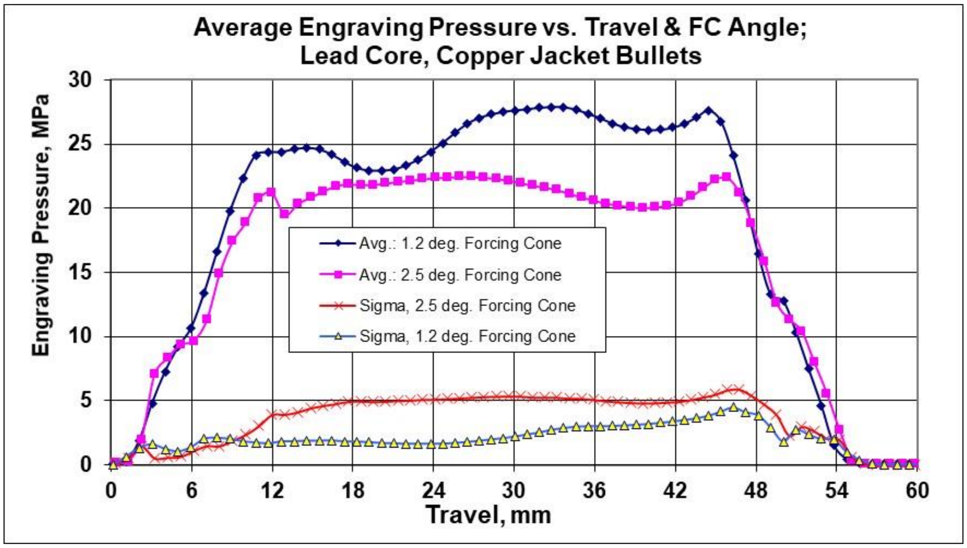

Figure 7: Forcing Cone Angle vs Engraving Pressure Mean and Sigma

Figure 7 shows increased average engraving pressure and decreased engraving pressure variation for the shallower (1.2 deg.) forcing cone compared to the 2.5 deg. Increased average engraving pressure will reduce variations in bullet motion early in the interior ballistic cycle, while decreased engraving variation will provide more consistent peak pressure, which translates to a reduction in muzzle velocity variability.

Barrel Boundary Conditions

How the barrel is restrained in the firearm influences how the barrel vibrates in response to the projectile passage. Virtually all bolt action rifles have some sort of recoil luge either sandwiched between the barrel and the receiver, or part of the receiver, which transmits the recoil force from the barrel to the stock in a repeatable location. Dedicated shooters sometimes do an aftermarket "glass bed" to the action of their guns. This involves spraying a release agent on the barrel, putting a fiberglass and epoxy mixture into the stock after creating a dedicated pocket for this goop in the wood, and letting the mixture set after screwing the barrel back into the action. This activity is frequently accompanied by "free floating" of the barrel, where any contact applied to the mid-barrel is mechanically removed. This allows the barrel to flex freely and expand due to thermal input from firing without contacting the barrel. It's my experience that these procedures may result in somewhat larger dispersion (group size) than which the rifle might otherwise be capable, but the impact point is more repeatable group-to-group because the dimensional variability of the wood due to temperature or humidity variations has been removed.

Contact near the mid barrel point by the end of the stock forearm is a typical of "production" rifles to reduce barrel vibration, and there are solid mechanical engineering principles behind this manufacturing approach to reducing the dispersion of a rifle. The incorporation of a contact point between the barrel and the stock reduces the barrel bending deflections from applied loads applied internally by the projectile to the barrel, reducing the bore pointing variability component of the dispersion error budget. A comparison between the support provided for a free floated barrel and one with forearm pressure applied by the stock is shown in Figure 8.

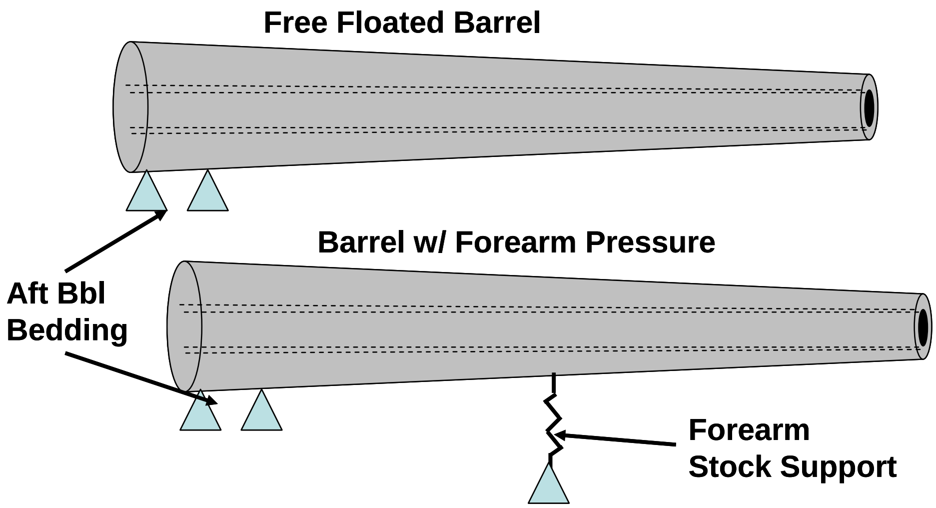

Figure 8: Comparison of Free Floated Barrel and Mid-Barrel Support

The incorporation of the mid barrel support should help reduce the deflection of the barrel caused by asymmetric load that arises from bullet CG offset multiplied by the bullet spin rate. This unbalanced load starts off very small and grows to non-trivial levels depending on the bullet weight, barrel twist, and projectile center of gravity offset. Figure 9 shows the lateral load vs. travel that must be reacted at the receiver or forearm for a 30 caliber bullet fired in a 30 cal/rev (1 turn in 10 inches) twist barrel with a 0.0001” center of gravity offset of the bullet with respect to the bore centerline.

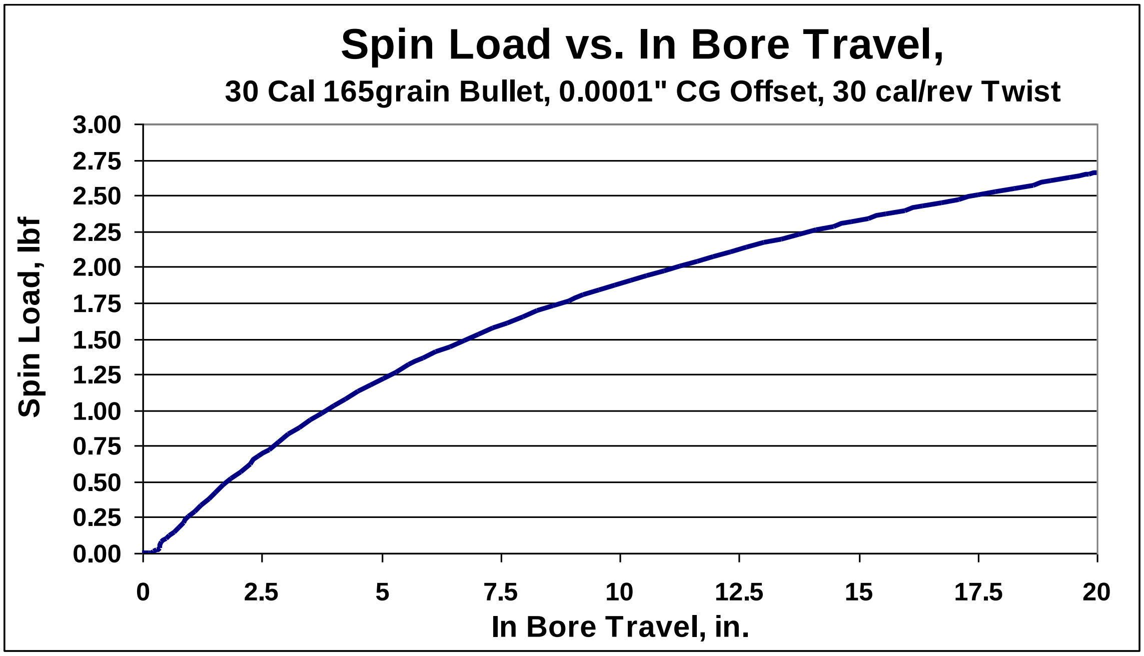

Figure 9: Lateral Load Caused By CG Offset & Projectile Spin

The forearm support reduces the deflection of the barrel due to the unbalanced load caused by the combination of projectile spin and center of gravity offset relative to the bore centerline. Forearm pressure can cause dispersion trouble if the barrel is tapered at the forward support. If the interval between shots is relatively short, the thermal input to the barrel will make the barrel grow in diameter and length and the external barrel taper leads to an increasing the pressure between the barrel and the stock forearm as the barrel grows in length. The increased load bends the barrel more than it was originally, causing an impact point shift. Since we're firing a series of shots, we see this as (most likely) vertical stringing. This is how free-floating may have an advantage in reducing barrel pointing variability shot-to-shot. Added to this effect is the sensitivity of the barrel to lateral loads due to a reduction in barrel elastic modulus as the temperature of the barrel increases with multiple shots.

It's my opinion that a material with low modulus of elasticity forming the contact at the forearm of the stock (e.g. Teflon sheet stock) is the perfect material to fabricate the forearm contact. If the barrel heats up and pushes harder on the contact, the contact "squishes" sideways, resulting in only a minor increase in load on the barrel, decreasing the impact point shift of the barrel.

"Harmonics"

Many people use the term "harmonics" to describe the transverse motion of a gun barrel in response to the internal passage of a projectile. While the typical barrel does indeed move in response to the projectile passage, this motion is best characterized by the term "forced vibration" instead of harmonic. Figure 10 shows the first three bending modes of a beam with "fixity" on the left hand side and otherwise completely unsupported (freely vibrating) otherwise. The first bending mode is known as the fundamental frequency, while the second bending mode is known as the first harmonic. Likewise, the 3rd bending mode is known as the 2nd harmonic.

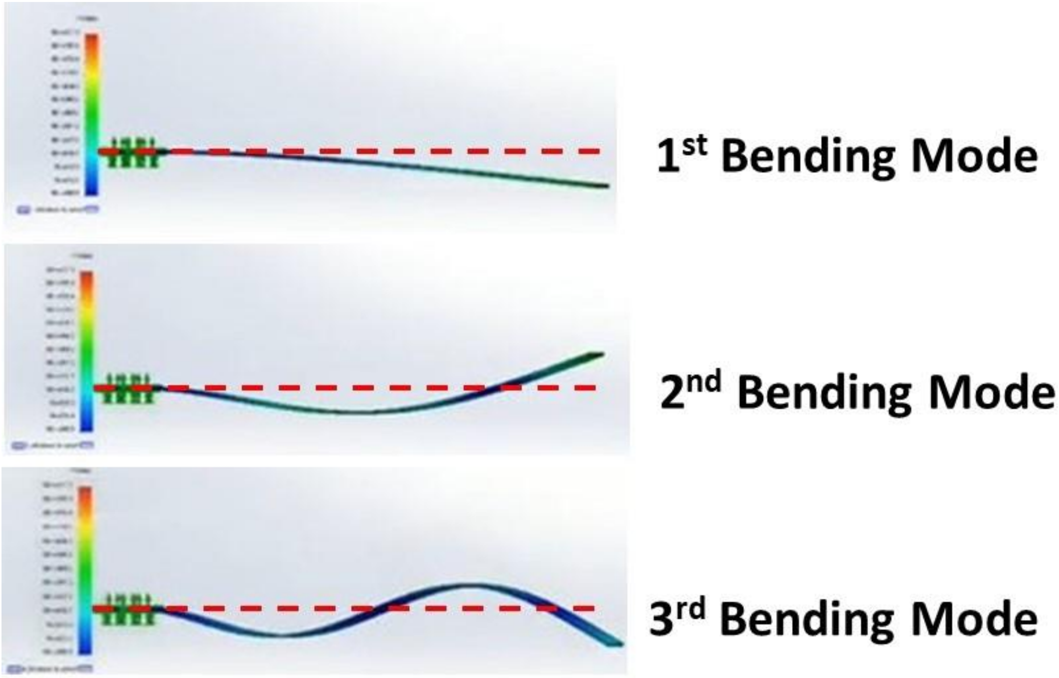

Figure 10: Beam Bending Modes

Using closed form calculations for the barrel with a 1.235” outside diameter at the breech, linearly tapering to 0.80” OD at the muzzle with a 0.304” internal hole through the barrel, it is possible to estimate the barrel fundamental and 2nd and 3rd bending mode frequencies. This can then be compared to the bullet spin frequencies if the barrel twist is constant and the barrel material is assumed to be steel, with known density (0.283 lb/in^3) and known modulus of elasticity (30x10^6 lb/in). Figure 11 shows a comparison of typical 30 caliber bullet spin frequencies vs. in-bore travel with the barrel structural bending modes for the geometry defined previously. Notably, the bullet spin frequencies do not intersect the barrel vibration frequencies.

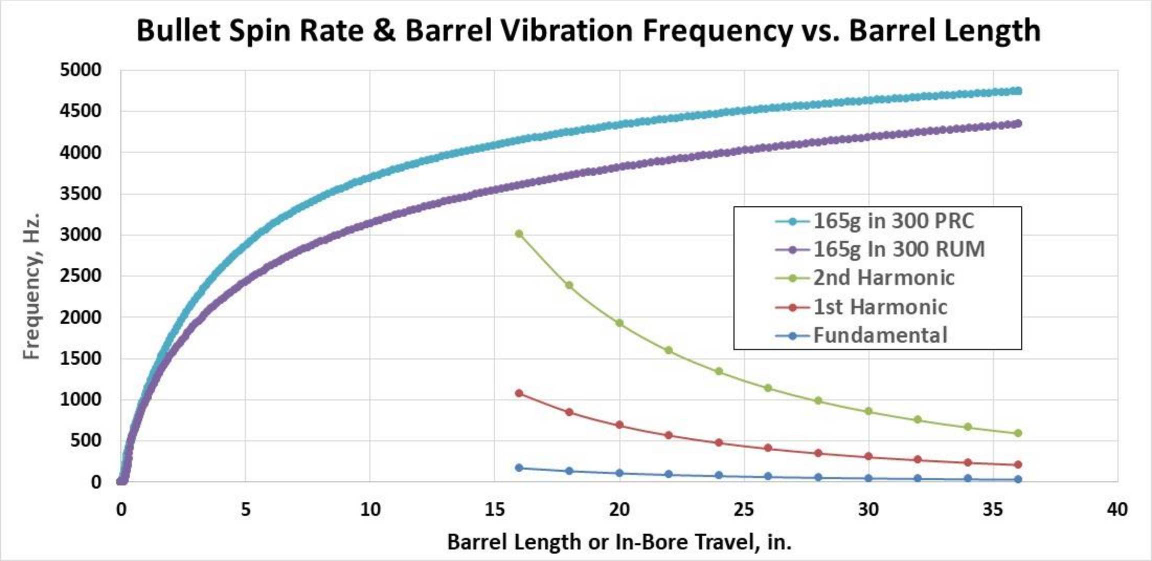

Figure 11: Bullet Spin Frequency & Barrel Vibration Frequencies vs. Barrel Length

Does that automatically mean there is no possibility of structural interaction between the bullet spin frequency and the barrel bending vibration frequencies? Let’s look at the vibration periods to better understand that possibility. Since the vibration period is the inverse of the frequency, it is a simple matter to compute the vibration periods (e.g. spin period) of the bullets as they travel down the barrel. Figure 12 shows the spin periods for the 300WM and 300 PRC firing a 165g bullet (they’re different because the 300WM has a 1/10” twist while the 300PRC has a 1/8.5” twist) contrasted with the 1st and 2nd harmonics (the fundamental frequency is off the top of the chart and is a non-player in this analysis). The bullet spin periods cross the first barrel vibration harmonic period at very short barrel lengths (~17-18 inches, a ridiculously short barrel length for a magnum cartridge), while the spin periods cross the 2nd harmonic (3rd bending mode) at a bit over 35 inches (considerably longer than useful length for anything except match guns).

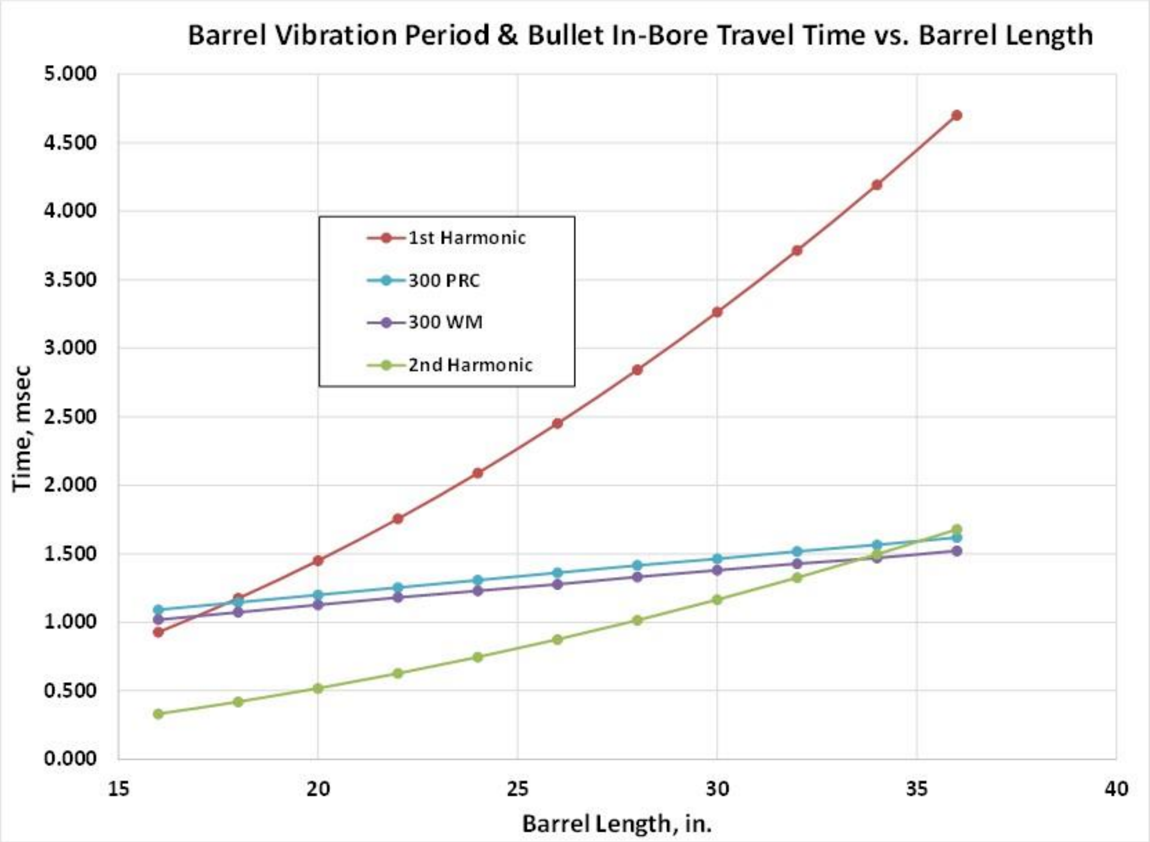

Figure 12: Barrel Vibration and Bullet Spin Periods vs. Barrel Length

So, if "harmonics" aren't likely to cause barrel transverse motion, is there some phenomenon that can? Yes, sadly. It's the dreaded "forced vibration" mentioned previously. How does "forced vibration" move the barrel? Figure 13 shows a barrel with the bore not concentric with the outside diameter, and the resulting bending moment applied to the barrel by the eccentric pressure applied at the instant the bullet is at the section indicated by the arrows.

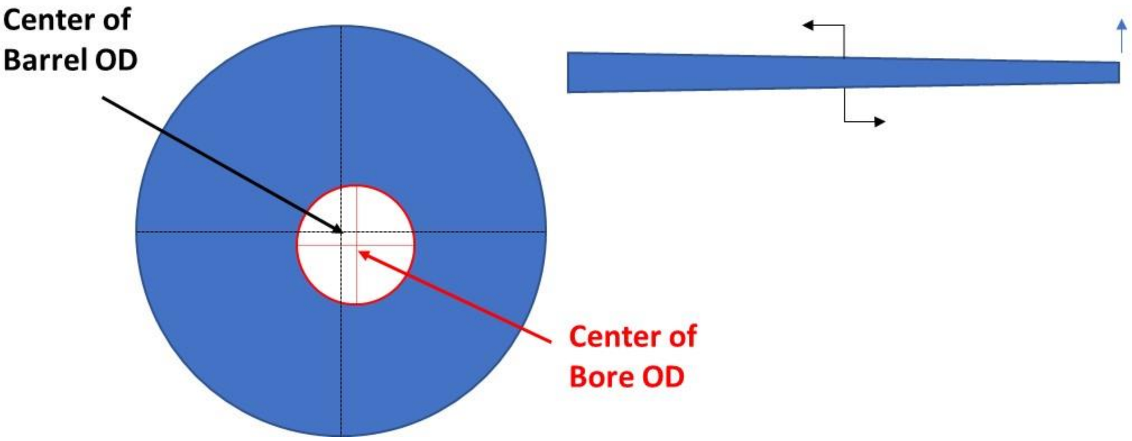

Figure 13: Barrel with Non-Concentric Bore and Barrel Bending Moment

A lack of bore straightness at the referenced section forces the bullet to follow a non-straight path, accelerating the bullet laterally, and Newton's 3rd law of motion dictates that force must be reacted by the barrel, causing it to move. So, there is a "double whammy" imposed on the barrel from a non-concentric bore: the eccentrically applied internal pressure bends the barrel, and the non-straight bore centerline forces the bullet to accelerate laterally, imposing a lateral force on the barrel which must be reacted at the receiver. Both factors contribute to the "forced vibration" influencing the bore motion.

Bore Straightness

All medium and large caliber barrels are straightened multiple times during their manufacture. This keeps the bore centerlines close to a straight line but can result in bore profiles that have the potential for several slow "kinks" in them. The blanks from which they are manufactured have residual stresses in them from manufacture. First, the blanks are center drilled and ground on each end to allow them to be gun drilled. Gun drilling is the deep hole drilling process used to plunk the hole through the length of the barrel blank. To make the hole as straight as possible, both the gun drill and the barrel blank should turn in opposite directions to each other during the drilling process. This minimizes the "wander" of the gun drill bit as it travels thru the blank. The gun drill bit is a specialized chip removal tool with an off-center hole that uses machining cooling fluid to remove chips from the cutting surface through the off center hole. Figure 14 shows an example of a gun drill bit used for machining holes in barrel blanks for small caliber guns.

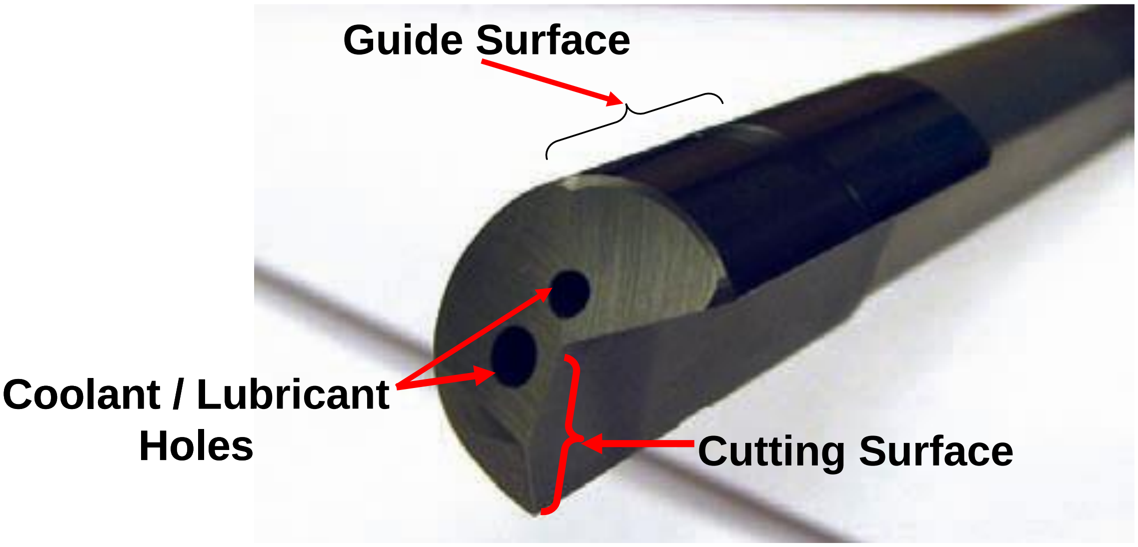

Figure 14: Small Caliber Gun Drill Bit

You are looking at the "business end" of the gun drill bit, the one that makes the chips and bores the hole in the length of the barrel blank. A coolant solution is pumped inside along the length of the gun drill shaft as the bit rotates. The cutting surface removes chips at the work face, and the guide surface prevents the drill bit from wandering too far off the intended centerline. As chips are created at the work face, the coolant flushes the chips along the length of the bit in the missing portion of the drill bit circle. Removal of the machined chips is as important as actually making the chips because if they are not removed quickly, the chips make the bit bind up in the barrel blank, and productivity suffers greatly.

For medium caliber barrels, the gun drill bits are a bit different geometry, using multiple cutting surfaces to remove the chips. In this machining process, the coolant is pumped around the outside of the gun drill bit, flushing the chips into the center of the hollow drill shaft and out for removal. Figure 15 shows a medium caliber gun drill bit.

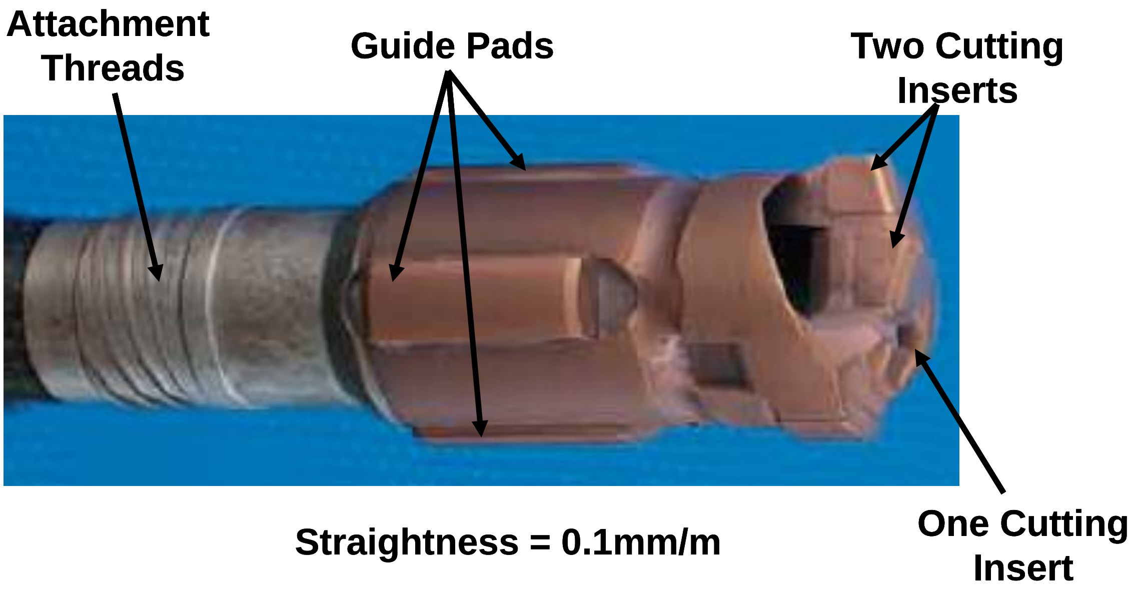

Figure 15: Medium Caliber Gun Drill Bit

The guide pads keep the drill bit contact the inside of the drilled hole, keeping the bit pointed in a reasonably straight direction. Since the guide pads aren’t solid around the whole bit circumference of the bit (we need to squirt coolant / machining fluid around the bit and guide pads anyway), there’s less chance of getting the bit “bound up” in the drilled hole. The chips cut off the machined bore are pushed into the hole seen in the upper right-hand side of the gun drill bit shown in Figure 15 by the machining coolant and are removed out through the hollow drill bit shaft. The bore created by the gun drill is called rough drilled, but rough drilled is a bit of a misnomer as some of these surfaces are wonderfully smooth given what’s been done to them.

For medium caliber blanks, bore “wander” of less than 0.001 inch per inch or 0.1mm/meter of hole depth drilled with respect to the exterior of the barrel blank is considered acceptable. In large caliber cannon caliber gun drilling, the position of the gun drill bit is constantly monitored with ultrasonic techniques and actively guided on a straight path using lasers to determine the position of the drill bit and piezoelectric transducers to steer it back to the intended path.

At this point, the gun drilled hole is most likely a long, slow bend, and when the through hole exits the end being driven by the chuck, it’s not in the center of the exterior of the chuck end. A mandrel is inserted in the center of the chuck end, and the exterior is then machined true to the gun drilled holes in each end. Grind spots are then applied along the length of the blank that are concentric to the gun drilled hole as determined by ultrasonic measurement equipment. Subsequent machining operations on the OD of the barrel remove material, some of which may contain residual stress. If residual stress on the exterior is removed, the once reasonably straight hole through the blank is no longer straight. Subsequent straightening operations are conducted, keeping the exterior of the gun drilled blank as straight as possible.

I've investigated the effect bore straightness has on targeting and dispersion in 20mm, having spent a bit over 7 years on the task. Let me say, unequivocally, that in medium and large calibers, lack of perfect bore straightness, by itself, is **not** a significant contributor to increased dispersion, provided the interval between shots in the same barrel is sufficiently long for barrel motion to damp prior to the next shot being fired. Bore straightness affects accuracy, where the mean point of impact for a group of bullets ends up relative to boresite, but the effect on dispersion is quite small. In medium and large caliber guns, you would need to fire many hundreds of bullets to statistically prove the effect bore straightness has on dispersion of the same lot of projectiles fired from a straight barrel vs. a "crooked" barrel, at a 95% confidence level.

I expect some increased dispersion sensitivity for small caliber projectiles to lack of perfect bore straightness compared to medium and large caliber bullets, but only in light of how action time (in-bore travel time) variability interacts with the barrel natural vibration frequency and the potential for sharp changes in bore centerline path to cause projectiles to leave deposits of jacket material behind in the bore, adversely affecting repeatability of projectile angular rates and barrel pointing as the projectile exits the bore. Detailed balloting models of small caliber systems shows the projectile cross velocity, whether arising from projectile Center of Gravity offset multiplied by spin, or from variability in barrel pointing at muzzle exit, accounts for 25-35% of the total error budget.

Having looked at the bore centerline straightness for hundreds of barrels and conducted balloting simulations on non-straight barrels, I can say there are "benign" bore shapes, and "problem" bore shapes. Benign bore shapes are half-sine waves with small maximum deviation. Conceptually, think of a perfectly straight bore bent only by gravity and the mass of the barrel. "Problem" bore shapes have a sharp discontinuity in bore path centerline near the muzzle (where the bullet has high velocity). Whether the problem bore shape causes dispersion (group size) problems largely depends on the bullet construction, it's structural response to the rapid lateral acceleration, and the "aerodynamic jump sensitivity" of the bullet design.

All barrel manufacturers do a wonderful job making barrels as straight as they can possibly be but having looked at the bore straightness of literally hundreds of barrels, I can say with great confidence that a perfectly straight barrel hasn't yet been made, and that goes for precision small caliber barrels as well. I've examined bore centerline data in 5.56mm, 20mm, 105mm, 120mm and 155mm in terms of calibers, and plotted the "worst case" bores as a function of caliber in Figure 16. The bore deviations shown here do not consider the effect of gravity, which tends to increase the bore deflections unless other provisions are made. There is a minimum in bore deflections in 120mm due to the way these barrels are made and the care with which they are straightened. These barrels also fire high performance APFSDS projectiles that have structures that are fairly sensitive to lateral accelerations, so great care is taken in shaping the bore of these barrels.

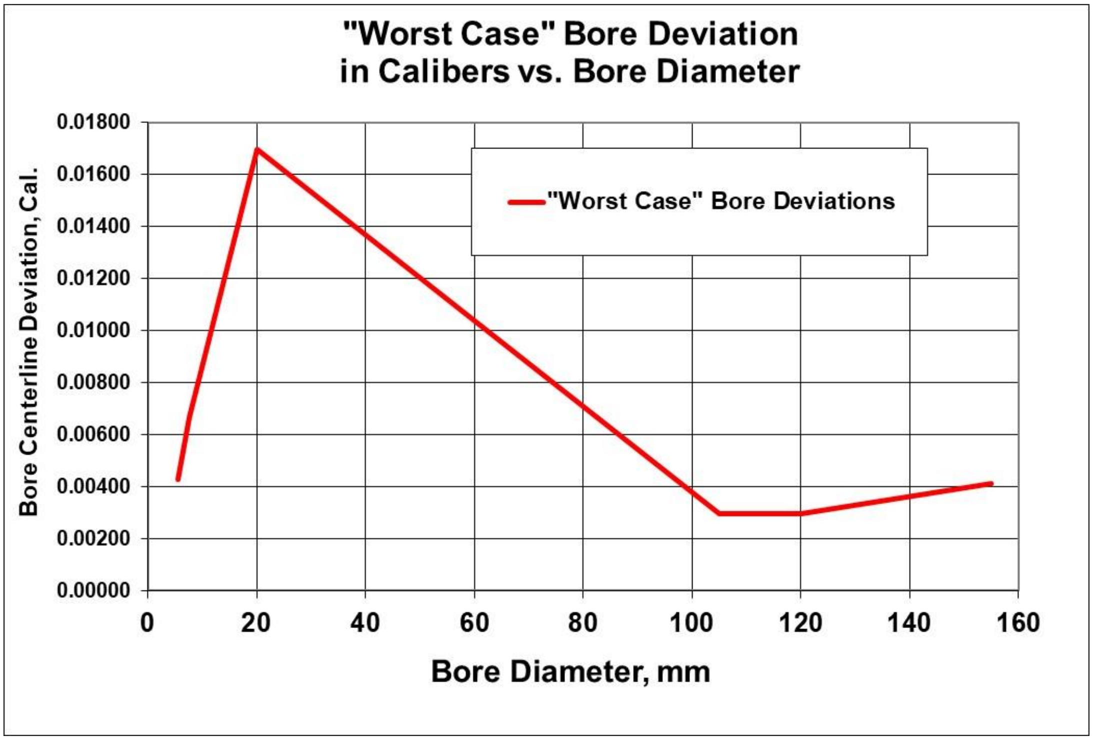

Figure 16: Worst Case Bore Deviations vs. Bore Diameter

Figure 17 shows some measured bore centerline path deviations (root sum square, or RSS) as a function of distance from the origin of rifling, both quantities expressed in calibers or bore diameters.

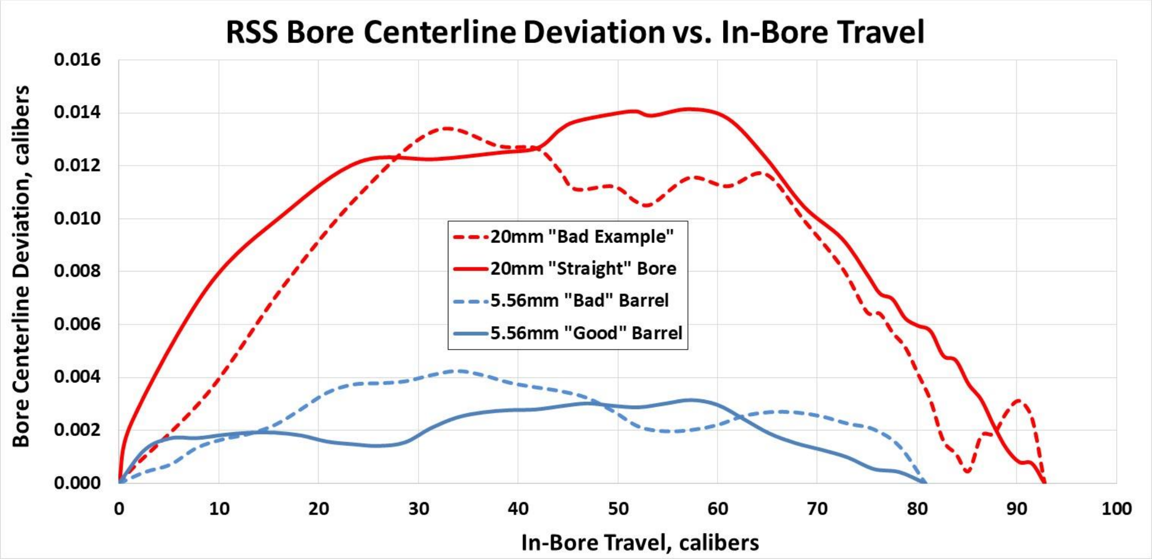

Figure 17: Measured Bore Centerline Deviations

The data shown in Figure 17 has the gravity droop removed from the bore center line path, so we're looking at the bore straightness as if we had the barrel pointed straight up or straight down. Clearly, the 20mm barrels are the least straight, and the 20mm "Bad Example" is exactly that. The gun in which this barrel is used is a multi-barrel gun (e.g. Gatling gun) with requirements that all the barrels shoot to the same mean point of impact, with the mean point of impact of the "worst case" barrel shooting no more than 1.5 mils from the measured center of the burst. All this targeting is done electronically, so each barrel can be separated from the others. But, while the "20mm Bad Example" barrel didn't have its mean point of impact particularly well coincident with its neighbors, the dispersion of ammunition about this barrel's mean point of impact was quite acceptable. This means that for this ammunition and barrel combination, there was no significant interaction between the ammunition action time variability and the natural frequency of the barrel as restrained in the clamps which tie it to the others in the barrel cluster.

Effect of Exterior Flutes on Barrel Performance

Some folks have grooves or "flutes" machined into the exterior surface of the barrels they use and there are a variety of reasons given for their use. Do they offer any performance benefits, and are there any drawbacks to using them on new, after market barrels, or applying the machining operation to existing factory barrels?

Aesthetics is a valid reason to use them, some folks not in the military like the looks of them. They do a fairly good job of reducing barrel weight; removing strategic portions of the exterior of the barrel is a good way to reduce barrel weight, if you're not using a composite wrapped barrel. The US military has used them for several decades on the M242 25mm "Chain Gun", as well as on the larger 30mm Mk44 gun. Figure 18 shows the exterior of an M242 "heavy barrel" Chain Gun with external flutes machined into the exterior of the barrel.

Figure 18: M242 Chain Gun Barrel with External Flutes

But do external flutes provide any group size reductions (frequently and erroneously called "accuracy improvement by gun writers) compared to a barrel without them? Are there any "snakes in the grass" with external flutes that might lead to undesirable performance changes?

If you're buying an aftermarket barrel with external flutes for the purpose of saving weight, be advised that you need to pick a barrel that has the flutes start well past the travel at which peak pressure on the base of the bullet occurs. The travel at peak pressure ranges from about 6-7 calibers of travel for light-for-caliber bullets, to about 3 calibers for heavy for caliber bullets. So, to be safe when machining external grooves in the exterior of the barrel, the barrel maker shouldn't start the grooves any closer to the chamber than about 7 calibers from the end of the case mouth.

Figure 19 shows an original equipment barrel with after-market external flutes split open after less than 100 firings because the flutes were applied too closely to the travel at peak pressure. The red arrow shows the signature of a crack of "critical depth" in the internal surface of the barrel. The external flutes reduced the fatigue life of the barrel in this section, resulting in the premature barrel failure. So, if you decide to acquire an after-market barrel with exterior flutes, you should ask the maker how (with what tools or testing) (s)he's used in deciding where to start the external flutes.

Figure 19: Failed 300 WM Barrel with After-Market External Flutes

In summary, the barrel exit twist selected, land and groove geometry, and forcing cone details all have the potential to influence group size.

- The barrel exit twist affects the gyroscopic stability and dispersion of the projectile and should be carefully selected to provide adequate spin for the longest bullet anticipated to be fired from the firearm.

- Polygonal land geometry appears to have a 8-12% dispersion benefit when it comes to shooting smaller groups, compared to standard rifling.

- Shallow barrel forcing cone angles are expected to exhibit a reduction in muzzle velocity variation compared to barrels with steeper forcing cone angles.

- Boundary conditions and bore straightness affect the barrel pointing via a "forced vibration", NOT "harmonics".

- There are "benign" and "problem" bore shapes. Whether the "problem" bore shape adversely affects bullet dispersion depends on the bullet construction, it's structural response to lateral accelerations, and it's aerodynamic jump sensitivity.

- If external flutes are to be used on the barrel, the location of these features must be carefully chosen to provide adequate fatigue life.