Name: Ross Lawson
Supervisor: PSS

To what extent does rifling affect the accuracy and design of modern rifles?

Abstract

The plan of my extended essay is to explore my interest in competitive small bore shooting by investigating the effect the invention of rifling had on specifically rifles accuracy. To do so I will look into the origin of the modern rifle, see how rifling is manufactured, compare the accuracy of early rifling and smoothbore, examine how important twist rate is to a rifles accuracy and then touch on the physics surrounding a spinning bullet in flight.

Introduction

In this essay I will explain how the spin that the rifling component applies on bullets has revolutionised competitive target shooting as well as military purposes. Rifling opened up the modern sport of target rifles which I am enthusiastic about and have an active role in teaching due to being captain of shooting at my school. Rifling is constantly being developed further with more efficient twist rates for a multitude of tasks.

Brief History of rifles and the invention of rifling:

Rifling is now commonplace in almost all modern forms of weaponry which involve projectiles of various forms ranging from .22 rounds all the way up to 122mm High Explosive artillery shells. "Rifling started to be used during the 19th century, however, its invention dates to the end of the 15th century when in 1520 August Kotter, an armourer of Nuremberg, Germany started work on the concept of rifling and true rifling (resembles that of today's closely) dates from the mid-16th century"*[1]. Although it was revolutionary when introduced to infantry firearms, it was not used for a long time due to many military commanders preferring smooth bore weapons for infantry as it was far cheaper and the rifling was not efficient for the type of ammunition. The concept that rifling brought was also not completely original as archers (primary ranged infantry for hundreds of years before hand) had long realized that a twist added to the tail feathers of their arrows gave them greater accuracy.

Russian 122mm shrapnel shell showing rifling

The concept of rifling and how it is manufactured:

Rifling was originally designed to reuse the phenomenon of feathers allowing arrows to be launched further and faster by bows of all categories. Crossbows also used feathers on their bolts, despite having in general much higher load weights than bows.

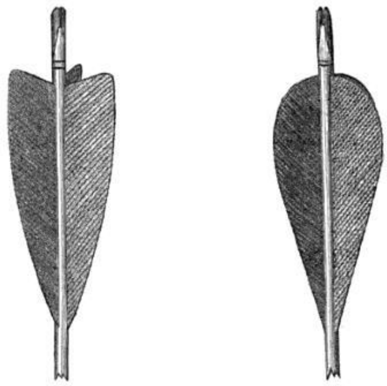


Fig. 12. Fig. 13.

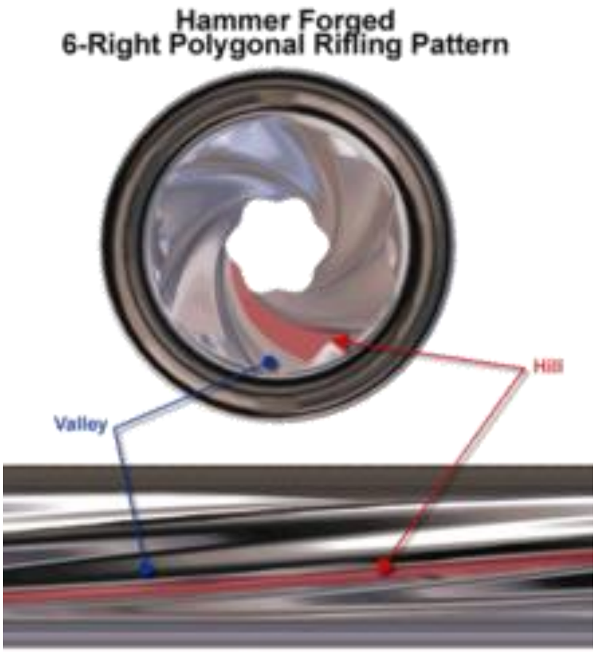
Since the dawn of gunpowder the concept of rifling also existed due to armorers experimenting with the similarities in traditional arrows and the new concept of lead ammunition.

"Rifling refers to helical grooves in the barrel of a gun or firearm, which imparts a spin to a projectile around its long axis. This spin serves to gyroscopically stabilize the projectile, improving its aerodynamic stability and accuracy"*[3]. It is now commonplace in almost all weapons that involve rounds that fire single projectiles (not shells which have multiple pellets inside). Most people recognise rifling from the famous James Bond barrel sequence at the start of every movie to date (picture shows rifling inside a cross section of a tank's barrel overleaf):

How the spinning effect is produced:

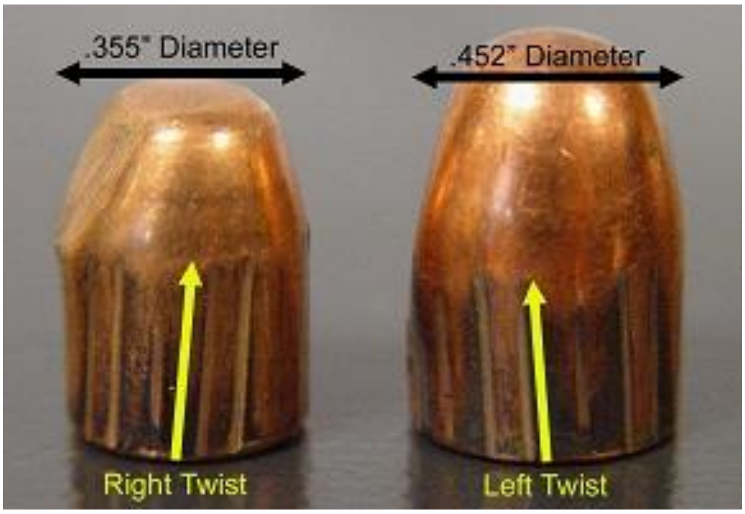
To produce the spinning effect the barrel lining and projectile have to match on several criteria. Firstly to produce the spinning effect inside the barrel the rifling is cut. The most common method to do this is by cutting one groove at a time with a machine tool. There are several other methods to create rifling with slightly different properties such as cutting all grooves in one pass with a special progressive broaching bit, this creates rifling to very similar quality but requires much larger machinery to do, therefore, it is usually used in large diameter barrels such as the tank barrel shown above.

The grooves are the spaces that are cut out, and the resulting ridges are called lands. These lands and grooves can vary in number, depth, shape, direction of twist (right or left), and its "twist rate" *[3]. The spin imparted by rifling significantly improves the stability of the projectile, improving both range and accuracy varying these qualities have effects on the projectile which can sometimes be favorable depending on its use. Usually rifling is constant down the barrel i.e. the bullet spins at a constant rate for the duration of the barrel, however, some firearms use "gain twist" which is where the frequency of turns increases from chamber to muzzle.



The diagram shows what a clockwise spin would look like by comparing a view down the barrel (top) and a cross section lengthways (bottom). The diagram uses more colloquial language for describing the components of the rifling ,"Hills" (grooves) and "Valleys" (landings).

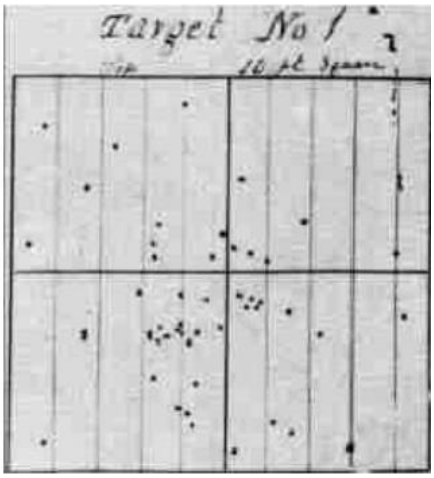
The casing and more importantly the bullets also have to be fitted to the rifling or else it is not efficient. Since the barrel is not circular in cross-section, it cannot be accurately described with a single diameter. Rifled bores may be described by the bore diameter (the diameter across the *lands* or high points in the rifling), or by groove diameter (the diameter across the *grooves* or low points in the rifling). In breech-loading firearms, the task of seating the projectile into the rifling is handled by the *throat* of the chamber. The projectile passes through the “freebore” (smooth circular diameter section of the barrel) and then the “throat angle” (where the throat transitions into the rifled barrel). The throat is usually slightly larger than the the intended casing so that it can be easily pushed into the firing postion and also because the projectile expands under the pressure of firing. The projectile itself will also have grooves cut often with a clockwise or anti-clockwise direction so that when it expands these fit flush into the rifling and an efficient spin is produced. Examples of bullets with directional grooves cut are shown overleaf:



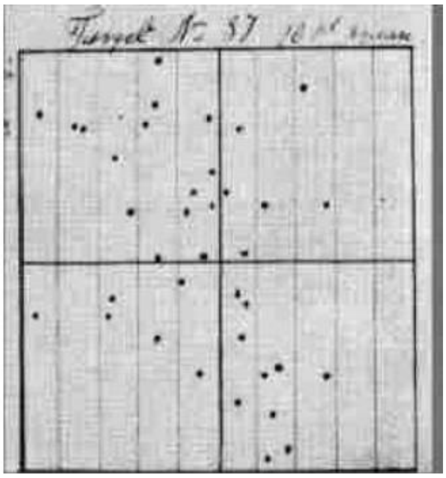
<u>How significant is the spin effect on the accuracy of the projectile?</u>

Old smoothbore guns, which were loaded with bullets that were spheres, they only had an effective range of about sixty yards. Modern rifles now have an average effective range far greater than this. It is obvious that the length of the barrel had much less relevance to accuracy in the past as muskets had an average barrel length of 40”, however modern small bore rifles have average lengths of nearly half that 26”-27”. This is owed to the development of rifling and the twist of modern projectiles.

To visually compare the difference rifling made to accuracy an experiment was conducted where a “New Rifled Musket, Calibre .58” (rifling very basic and did not use Miller twist rule) fired 50 times and out of 50 shots red, 48 hit, an accuracy rate of 96%: *[4]

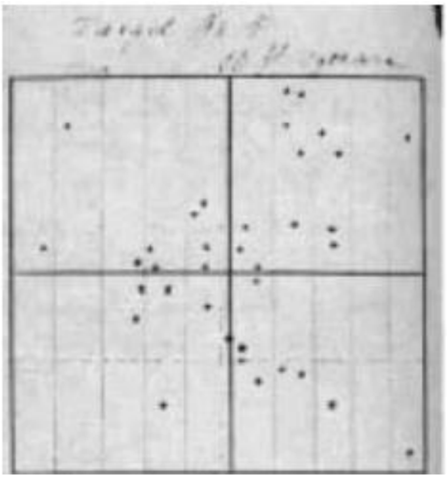


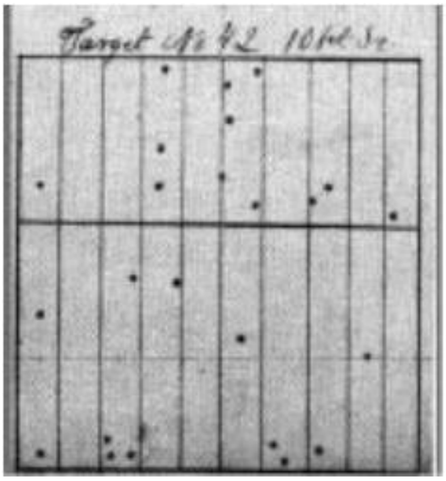
The second target is for the “Smooth bore musket, calibre .69." Out of 50 shots red, 37 hit, an accuracy rate of 74%, this is less than the rifled musket but not as much as one would assume. It is 77% as accurate as the rifled musket:



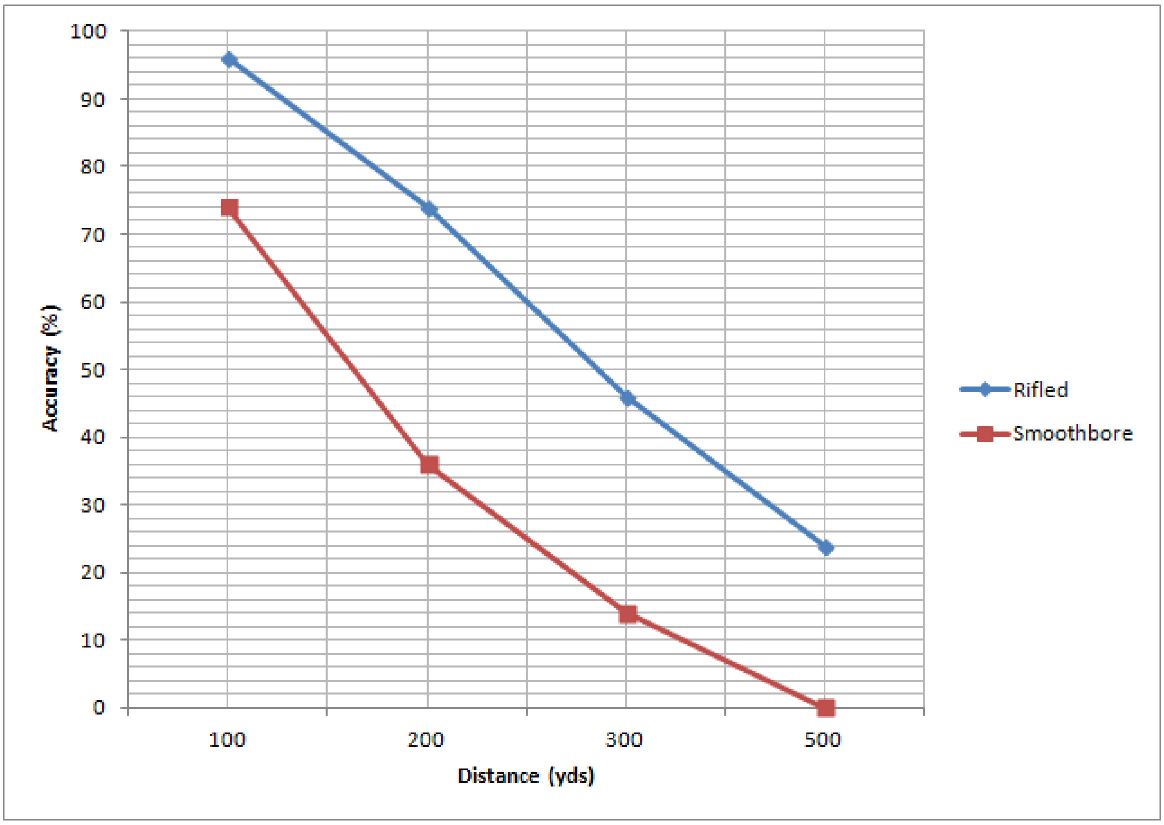
Upon first glance one may assume that actually the difference the new technology of a rifled musket made was negligible in respects to the much greater cost in manufacturing and of the ammunition. However, The range for these two targets was only 100 yards. Taking it up to 200 yards starts to show the fall off in effective range of smoothbore weapons.

The third target is for the “New Rifled Musket, Calibre .58." Out of 50 shots red, 37 hit, an accuracy rate of 74%(left image). Whilst the same smoothbore as fired prior out of 50 shots fired, 18 hit, an accuracy rate of 36% (right image), which is 48% the accuracy of the rifled musket at this range. This shows a 29% decrease in accuracy compared to the rifled musket by only a 100 yard distance change which represents that there is a great drop off in effective range for these smoothbore weapons.



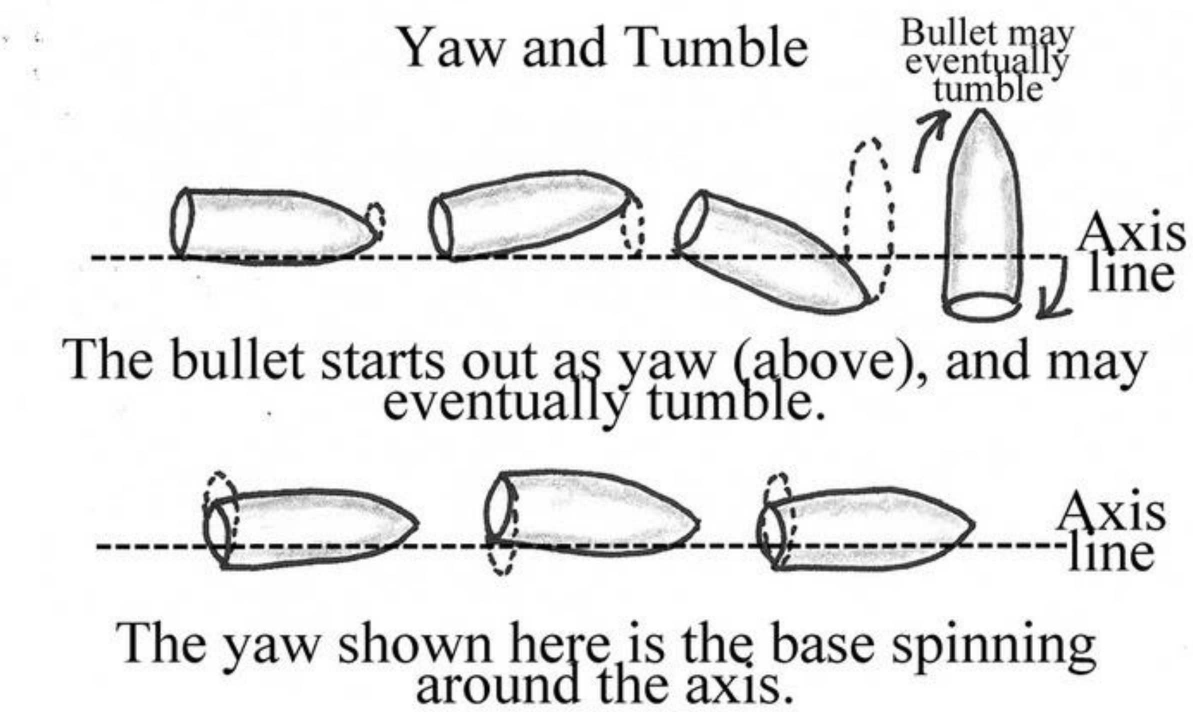


The trend continues as at 300 yards the rifled musket hit 46% and the smoothbore only 14% making it very ineffective at that range. This is another 29-30% decrease in accuracy. At 500 the smoothbore failed to hit the target whilst the rifled musket still hit 24% of the time. These results not only show that rifling was far more accurate at range, but also did not suffer as significant drop of range as the smoothbore. For the smoothbore to not hit at all it was very likely the musket balls had fallen short of the target, and the rifled musket shots were due to its inaccuracy at such a long range not that they were dropping off.



The graph shows how the non-rifled firearm suffers from a much greater decline in accuracy over an increase in range; however, this can be made even more distinguishable when the optimum amount of "twist" is used.

The obvious outcome of these tests is that rifling was far more efficient, especially at greater ranges where it withheld its accuracy much better than smoothbore. To understand this better one must understand why the spin does affect the projectile in a favourable way. The rifling on a gun barrel twists the bullet during its flight out of the barrel when it has it's highest velocity so that it spins as it flies. If the bullet doesn't spin as it flies,it would make modern ammunition useless and the old type of non-aerodynamic sphere's would be used which have a much larger surface area. This surface area causes increased drag so the kinetic energy is lost from the projectile faster as primarily heat. The sphere shape of the old projectiles also lead to significant issues caused by the magnus effect which we will discuss later. If modern ammunition were used without a spin there would be few forces stabilizing the bullet and a tumble effect will be caused making it ineffective.. You can see this with any symmetrical oblong object. (concept illustrated below*[5]:)



If the bullet is spinning forces come into play that stop the bullet tumbling like above. The main one of these forces is angular momentum. The lower diagram shows a bullet flying in a much straighter orientation and does not flip. This is due to the spin applied along the axis of flight. “In simple terms when the bullet has some spin, it has some angular momentum in the direction of its motion. This spinning adds stability, because the bullet itself doesn't want to turn on another axis, this changes the direction of its angular momentum, so it stays pointing straight. Since it stays pointing straight, it is more aerodynamic, so it flies for longer”.*[6] For the spin to have the desired effect the twist equation is used in modern rifling and maximises efficiency.

Twist rate:

For the spin of a projectile to be efficient and have the best effect, the barrel should have a twist rate sufficient to spin stabilize any bullet that it would reasonably be expected to fire, but importantly not more than that. This optimum twist is calculated using miller’s twist rule in modern gunsmithing. This uses the twist rate of the bore and is expressed in several different forms. One way is in terms of the 'travel' (length) required to complete one full projectile revolution in the rifled barrel. It can be shown as a ratio via this equation:

$$Twist = \frac{L}{D_{bore}}$$

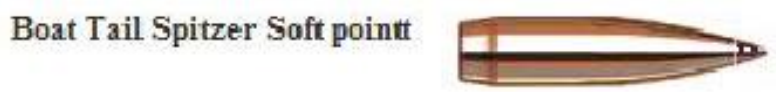
- Twist = twist rate expressed in bore diameters
- L = the twist length required to complete one full projectile revolution (in mm or in)
- D_{bore} = bore diameter (diameter of the lands, in mm or in)*[7]

Note that it is a ratio so any measurement can be used for the length and diameter as long as it is constant. Once this has been worked out you can then use it in Miller’s Twist Rule. There are two equations widely used to work out the optimum rate of twists being: Miller’s own equation and also Greenhill's formula

“In 1879, George Greenhill, a professor of mathematics at the Royal Military Academy (RMA) at Woolwich, London, UK developed a rule of thumb for calculating the optimal twist rate for lead-core bullets.” *[8] This equation does not account for the shape of the bullet as it only accounts for the bullet’s length and therefore is only relevant to cylindrical ammunition (old artillery projectiles such as the artillery shell shown earlier and the earliest developments of bullets similar to those nowadays i.e. similar to the modern round-nose.).

this is because in Greenhill's equation the bullet is considered as a cylinder. A round-nosed bullet is more like a cylinder, has its weight very evenly distributed along its entire length and takes less spin to stabilize. On the other hand, a spitzer-shaped bullet (contrast shown below) has most of its weight contained within the base half of the bullet. The center of mass is therefore not the middle of the bullet and it will require more spin to keep the nose and base aligned. However, if the velocity of the projectile is large enough the shape of the projectile to these extents has a largely reduced effect.

As visible the spitzer narrows around half-way down the bullet and this is what changes the weight distribution and makes the miller twist rule less accurate, unlike the round nose.



This highlights the main issue of the Greenhill formula as it is more suited to bullets from another era, where the bullet shapes were more cylindrical and largely made of lead alone. Modern bullets are longer (e.g. spitzer or boat-tail shape) and made of multiple materials (such as copper and brass jacketed, steel core etc.). Therefore Miller's own equation published in 2005 (Greenhill 1879) is more suited and accounts for the changes in shape and velocity. We will look at both to draw comparisons.

The Greenhill equation is as follows:

$$Twist = \frac{CD^2}{L} \times \sqrt{\frac{SG}{10.9}}$$

- C = 150 (use 180 for muzzle velocities higher than 2,800 f/s)
- D = bullet's diameter in inches
- L = bullet's length in inches
- SG = bullet's specific gravity (10.9 for lead-core bullets, which cancels out the second half of the equation)*[7]

N.B. "Specific gravity is the ratio of the density of a substance to the density (mass of the same unit volume) of a reference substance. The reference substance is nearly always water at its densest (4°C) for liquids and for gases it is air at room temperature (21°C). Pressure is nearly always 1 atm (101.325 kPa). A list using these criteria shown" (definition)*[9]:

Material	Specific Gravity
Water	1
Copper	8.96
Lead	11.35

Using this method to find the twist rate for the 5.56 x 45 mm calibre weapon, and has a muzzle velocity of 940 m/s which is used in the L98A2 Cadet GP Rifle (used by cadets including myself nationwide.) To simplify the projectile is counted as lead-core, although this is not completely true for this ammunition it will not affect the value significantly.
C=180 (940 m/s = 3090 f/s)
D=0.22in
L=0.76in
(180x0.22x0.22)/0.76= 11.46 = 1 turn in every 11.5 inches. This is not very close to the official value of 1 in 9 and highlights its shortcomings.) Taking into account the mixture of brass and lead modern ammunition is made out of the value is still only reduced to around 11 turns.

Miller's equation on the other hand is as follows:

$$t^2 = \frac{30m}{sd^3l(1+l^2)}$$

where:

- m = bullet mass in grains
- s = gyroscopic stability factor (dimensionless)
- d = bullet diameter in inches
- l = bullet length in calibers
- t = twist in calibers per turn

Given those definitions we can expand:

$$t = \frac{T}{d}$$

where T = twist in inches per turn, and

$$l = \frac{L}{d}$$

where L = bullet length in inches.

Doing the calculation for the 5.56 again we get:

- m = 64grain

- s = 2.0 (the safe value noted above)
- d = 0.22in
- l = bullet length in calibers
- t = twist in turns per inch

$$l = \frac{L}{d}$$

where L = bullet length in inches → 0.76/0.22= 3.46

Therefore manipulating the equation we can find out the value for t*[7]:

$$T = \sqrt{\frac{30m}{sdl\,(1 + l^2)}}$$

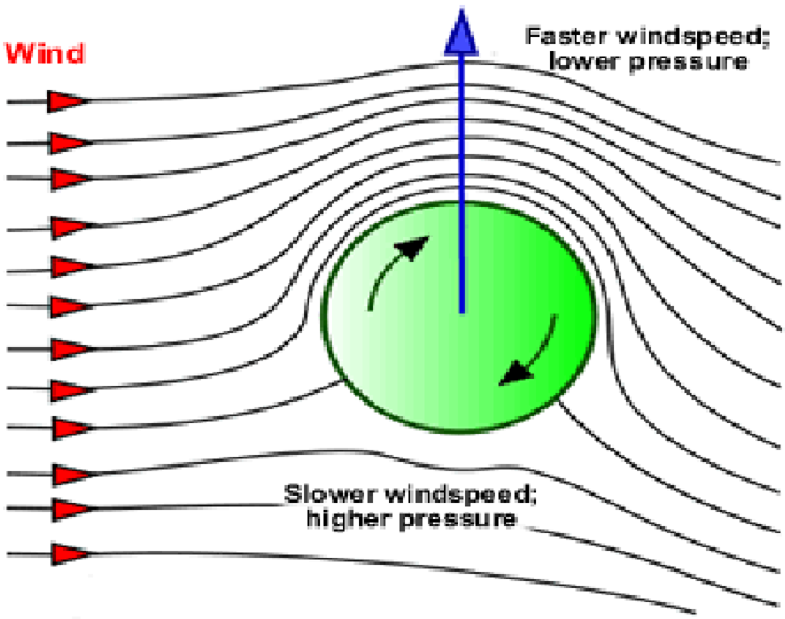
=sqroot((30x64)/(2x0.22x3.46(1+3.46^2))= 91.90(sqroot)= 9.59 turns per inch. This is much closer to the expected value of 1 in 9 inches and shows how the Greenhill equation is outdated. And also how the shape of the bullet and its changes through the years in design required rifling to adapt. Getting the amount of turns per inch is very important, if the twist rate is too low then the accuracy and range of the projectile will be significantly reduced. If it is too high it is arguably worse as the rifling will undergo a lot more stress and ware as the bullet will be spun at very high speeds. This will cause damage to the rifling making it ineffective and counterintuitive over time as well as reducing range and accuracy.

<u>How the spin effects the bullet during flight</u>

Now that we understand that rifling is a vast improvement over smoothbore in accuracy and that there is an optimum amount of twists for the calibre of round we can also examine how the spin effects the bullet favourably in flight. Most factors to do with the effect wind and air resistance have on projectory are only involved at long distances, this is due to the high velocity of modern projectiles making the effect of these factors negligible. Nevertheless they do play a part hne the velocity starts to drop off at longer ranges.

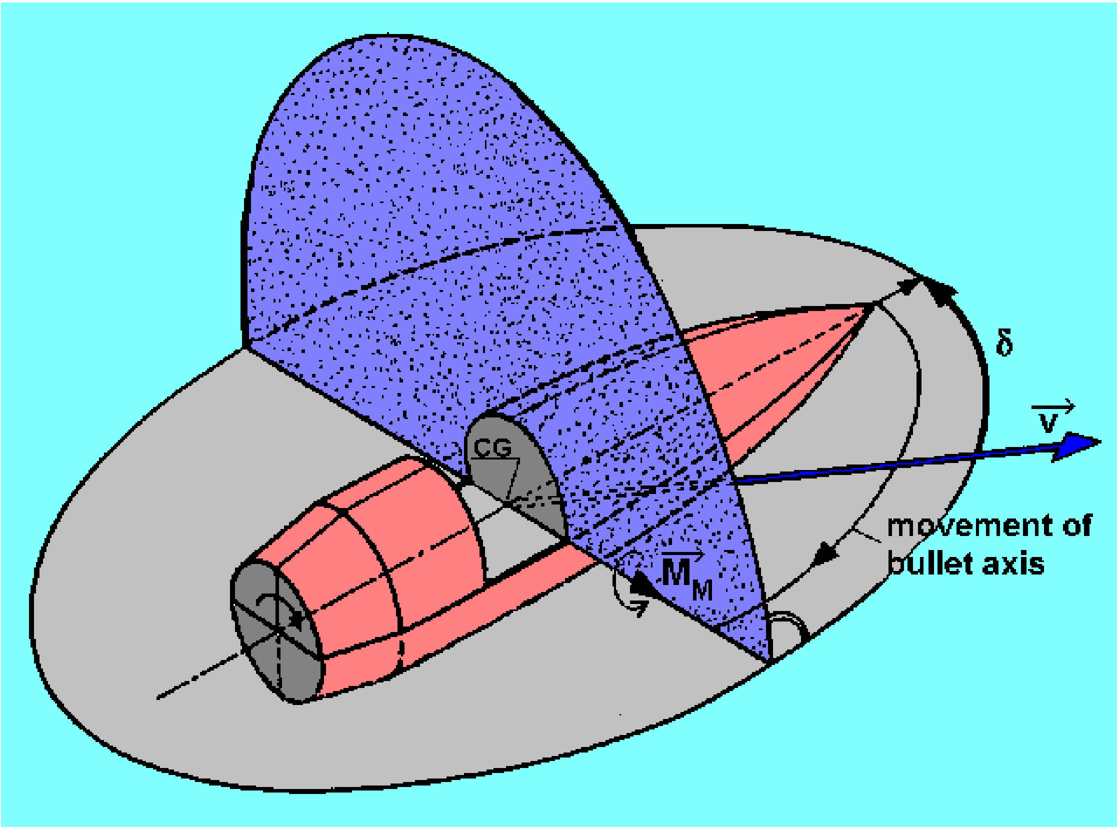
The first force that acts on a bullet spinning during flight is commonly known as the magnus effect. However, saying that it shows results identical to the common paper dropping experiment to demonstrate the magnus effect would be wrong. It is instead referred to as spin drift in shooting.

The magnus effect is put to common effect in most sports and has led to some of the best golf shots and football goals. It refers to when "A spinning object moving through a fluid departs from its straight path because of pressure differences that develop in the fluid as a result of velocity changes induced by the spinning body."(*10) Using an example of a football, the ball will be kicked and given a direction to spin in. This spin will drag some of the air around with it causing an area of low pressure and an area of high pressure. This will make the ball deviate from it's given straight path as it moves towards the region of lower pressure (illustrated*11) in this case it will rise:



However; saying that this is what happens to bullets would be incorrect. This is mostly due to smaller projectiles travelling at very high velocity so under 100m it has little effect on the path of the bullet. It does have significant effect after it has lost it's initial momentum. Because a bullet is not spherical it means that the effect it has is not as simple and obvious as for when it happens with a ball. In the case of old musket ammo which tended to be ball bearings, the magnus effect did exist and "hop up" of rifles was noted to take place in certain conditions where the ball would hit above the marking place and also once they peeked would fall at a much greater rate due to gravity and loss of velocity due to the friction of the air being dragged around with the shot. Modern bullets are not spherical as spoken about earlier.

On modern bullets the magnus effect can either stabilize the bullet causing it to fly straighter, or destabilize it and cause it to have a drift off effect. The effect is best explained with help of a diagram *[12]:

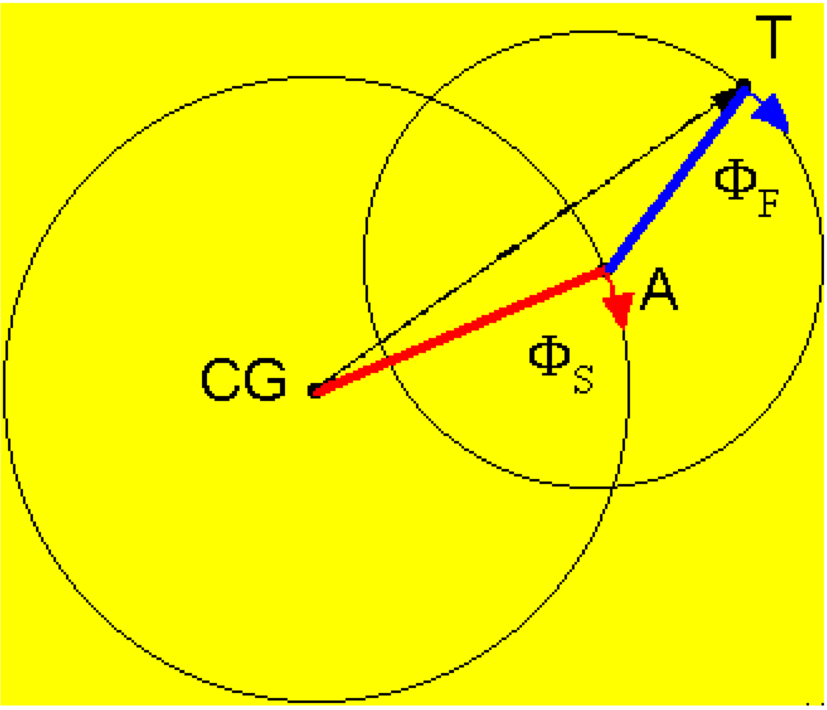


The diagram shows a bullet mid flight travelling along its longitudinal axis towards a target. The spin is illustrated as being clockwise, theoretically this would lead to a "magnus moment" which acts perpendicular to the longitudinal axis. This moment tries to rotate the bullet about an axis, perpendicular to the longitudinal axis of the bullet. It is important to note that in this diagram the force is acting at the centre of pressure for the system (where the forces of the air resistance are taken to act) and the bullets center of gravity (CG). If these conditions are met the moment will stabilize the system and will decrease the angle of yaw δ as shown in the diagram. If the centre of pressure is in front of the centre of gravity it will instead destabilize the bullet and increase the amount of angle of yaw. This is due to the gyroscopic effect that the bullet generates if it is spinning fast enough. If the spin is insufficient then the magnus effect will always be unfavourable. To conclude the magnus effect, for bullets the effects should not be seen as one that directs it off course but instead is favourable as it is an important moment in the bullets system that helps stabilise it and is another reason why getting the optimum spin rate is very important.

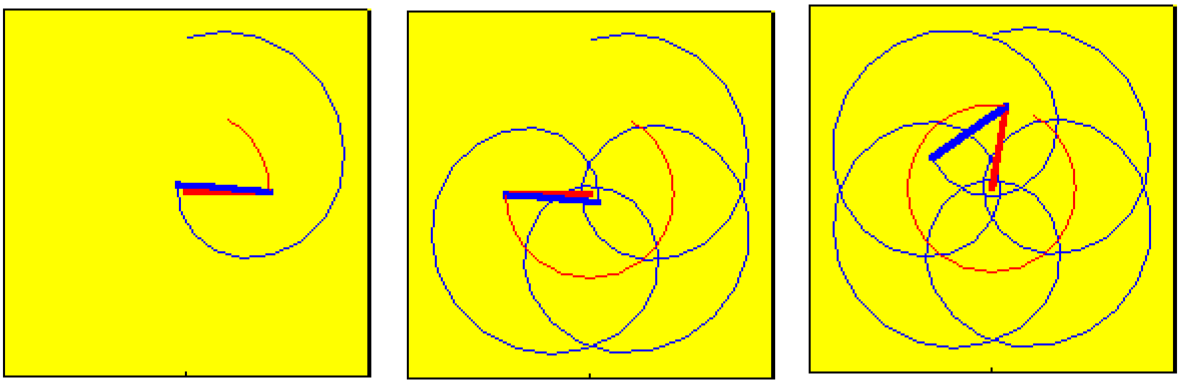
The other main force generated by the bullet's spin and the air resistance is another moment being the spin damping moment. Put simply it is just the effect of the friction between the surface (mainly the face) of the bullet and that air. The most important factor is not that it decreases the velocity of the bullet but instead that it reduces its spinning motion (i.e. the rate at which the bullet spins). This is vital as if the bullet's spin was not slowed then it would become inefficient in the system as the bullet loses velocity. The spin will be destabilising and could result in drifting away from the target in the direction of its spin or even a tumbling effect.

Along with these forces caused by the spin there is also forces that can be expected to oppose any motion. Gravity acts from the centre of mass causing the bullet to lose height as well as centrifugal force which is negligible due to its upwards movement being counter acted by gravity which despite bullets being very light is still a much greater force due to bullet's streamlined design. There is also a force called the Coriolis force which due to it being so small we can ignore (it is commonly only appreciated for artillery shells travelling over 20km.

All these forces and moments acting on the system of the travelling system result in a unique model called the "two arm model" *[13]:



The diagram illustrates how a spin stabilised bullet does not actually travel in a perfect line towards it's target but instead oscillates by tiny amounts in a specific fashion. CG and A can be imagined as two clock faces. Both are turning in a clockwise direction. CG is turning at a slower rate to A resulting in a pattern as follows:



If the system is unchanged the pattern will repeat in a near identical fashion until the projectile is stopped. Although the image portrays the bullet as being wildly inaccurate it is a much better method and smoothbore predecessors. The movements are actually very small and will not have a great effect on the end position of the round, at very large distances it does have a greater chance to miss the target but this is more likely to be shooter error than the the spinning motions fault (especially on high calibre weapons designed for the long ranges that are being spoken of as the velocity is so high they can travel as far as you could realistically desire). However, despite being much more accurate than smoothbore equivalents it still leaves a small amount of error and randomness in accuracy. This is why lasers are still being actively researched in terms of an effective warfare weapon as they experience none of the force a bullet does and therefore could theoretically be 100% accurate.

This brings us onto our last discussion that is how the shape of the bullet or projectile effects it's capability to be stabilised. Now we have looked at how the gyroscopic inertia works in unison to stabilise the projectile we can pick up on angular momentum again and this will tell us that larger projectiles are easier to spin stabilize as they have a larger radius meaning that there is more angular momentum gained (F=ma). This means that once spinning it will take a very large force to dissuade them off track. The length of bullet is also important, longer bullets which are common in warfare are much harder to spin stabilize as they are usually back heavy so the centre of pressure as touched on before can act unfavourably so a higher velocity is required to counteract this. This gives in terms of moments the drag force and other aerodynamic interference a longer “arm” or moment to act on. However, the longer shape is desired as the reduced drag greatly increases range whilst maintaining velocity to be effective.

Summary

In Summary, the “invention” of rifling was not actually an original idea as feathers had been used on arrows for hundreds of years before hand. Riflings use was also delayed due to cost over coming it’s edge in efficiency. It was when an efficient twist rate was established it started to become used.

The manufacturing of rifling is achieved in numerous ways, the most common being “machining”. The direction of the rifling is also important as the direction of spin does make a difference in calculations.

From original tests on efficiency of rifled guns against smoothbore of similar calibre, rifling came out easily on top and maintained accuracy much better than smoothbore. This was without the twist rule which would show an even greater division. However, riflings’ use was delayed due to it’s cost.

The twist rate is very important for a rifles accuracy as well as its maintainability. A unique twist rate is given to each calibre of ammunition as it is the modern round that is the decider of the twist rate instead of the type of rifle. Calibre’s are designed to closely fit into the rifling to be given this efficient spin and if the rate is too slow or fast can have great effects.

The bullet in air forms a very complex system where every moment acting around the bullet’s centre of gravity works together to stabilise the gyroscopic effect the spin of a bullet has. The three dimensional nature of the system is very complex and the bullet’s spin is crucial to this as a rotational moment of the spin being too great or small will result in a counterintuitive destabilising effect, this reduces the effective accuracy and range.

The effect the spin has on the bullet came to great surprise to me as it forms a truly unique pattern and disproved my naive theory that a bullet was mostly only affected by gravity acting on the bullet to bring its straight projectory down. There is a lot more than that occurring at all times during a bullet’s flight.

The shape of bullets is also vital. Despite older generation of projectiles having a larger diameter allowing for the spin stabilisation to occur more easily, rifles are tending to shoot longer bullets due to greater accuracy and range.

Conclusion:

To conclude, the use of rifling in firearms has greatly increased the range and accuracy of all firearms ranging from small bore .22 rifles that I use at school all the way up to large artillery shells designed to fire over 20km. In early experiments the difference in accuracy of rifled muskets to smoothbore were 33% more accurate than it's counterpart within effective range for both of them. At longer ranges the smoothbore muskets fell off at an average of 30% per 100 yards which is huge. The spinning effect the bullet has harnesses the air resistance and wind vector to stabilize it instead of being deviated off target like old rifles did. Rifling has made weaponry so accurate nowadays that it is hard to perceive a way in which to make them more effective without completely revolutionising projectiles by the introduction of technology such as lasers that can be pin-point accurate.

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