Moment of Inertia in Golf Club Design

Ron Brown

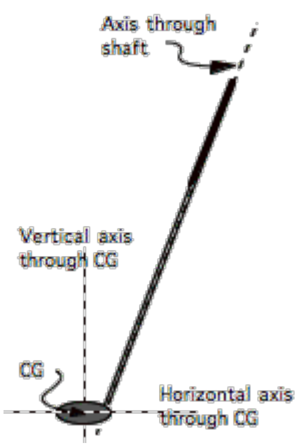
The buzz-word in golf club design - and in particular in drivers, is *moment of inertia*, or MOI. What is that? And why is it so important? Is it just a marketing thing - like horsepower or number of cup-holders? Or is there something fundamentally important about this esoteric concept that so many engineers struggled with in their freshman physics courses and now are consumed with in golf club design?

Moment of inertia. The key word here is "inertia" Actually, it is a word that means essentially the same thing colloquially as it does technically - that is, it is the property that makes something reluctant to change what it is doing or how it is moving. In the normal everyday use of the word, *systems* or *institutions* - like Congress or universities, or large corporations, or society itself - are said to have a lot of inertia since they cannot change their behavior quickly. They always continue doing what they had already been doing. The technical meaning of the word is largely the same - the inertia of an object is its resistance to changing its motion. For an object traveling in a straight line, the measure of the inertia of the object is just its mass. The greater the mass (hence its inertia), the greater the force required to change its motion - or accelerate it. (That, it turns out, is the meaning of Newton's famous second law of motion which is written $F=ma$ - *i.e.*, the force required to accelerate an object an amount a depends on the mass of the object.)

For objects that rotate about an axis, the term *moment of inertia* is the measure of the reluctance of the object to change how rapidly it is rotating. It is much easier to set a golf ball spinning about its vertical axis on a tabletop than it is a bowling ball because of the much larger rotational inertia - or MOI - of the bowling ball. And there are two reasons for that large moment of inertia, as we will see. The moment of inertia is a more complicated concept than just the mass of the object. It's true, the larger the mass the more difficult it is to start it rotating because of the larger moment of inertia. But the moment of inertia also depends on how that mass is distributed relative to the axis about which the rotation occurs (and it is this point that makes MOI in golf club design such a difficult idea to grasp). The farther any given mass is located relative to the rotation axis, the larger the rotational inertia about that axis. So the above bowling ball is not only much more massive, but that mass is also much farther from the axis of rotation than for the golf ball. Several other examples come to mind. If a pendulum is made by attaching a ball to a string, the longer the string (*i.e.*, the farther the mass is from the pivot point about which the pendulum rotates) the larger the moment of inertia and the pendulum swings much more slowly when released. To set a rotating platform spinning is much more difficult if the platform is loaded than if there is no weight on it. But it is even more difficult if that load is located near the edges of the platform rather than toward the middle. That is because the moment of inertia of each part of the system about some axis depends on the mass of that part multiplied by the *square* of the distance of that mass from the rotation axis. And the total moment of inertia of the entire system about the axis is just the sum of all the individual moments of inertia of all the parts that make up the system. The calculations can be very complicated, in general, even if one knows the mass, size, and shape of the object. Even for very symmetric objects, the calculation is often a problem in multivariable calculus. And it's even worse than that: Change the axis of rotation - even a little - and the moment of inertia is changed as well. MOI depends on how the mass is distributed relative to the axis of rotation being considered. And that raises yet another point - especially true for the golf club: Any object has as many moments of inertia as there are possible axes of rotation. That is, MOI is not just a property of the object, but rather depends on both the object and the rotation axis of interest.

So how does all of that apply to golf? In lots of ways, actually. That is, the mass of a golf ball (about 46 grams) is a measure of its inertia relative to straight-line motion. So the mass determines the force required at impact to accelerate the ball from rest to its launch speed as it leaves the clubface only a fraction of a millisecond after initial impact. (The acceleration is huge which means the force at impact is huge - thousands of pounds of force during the short time of contact!) But rotational inertia - or MOI - is much more complicated.

There are perhaps five different rotation axes that are of some interest in how a golf club behaves - hence five different moments of inertia to think about. But only three are significant in the design of a golf club. There is, of course, the obvious large sweeping club rotation associated with its motion in the swing plane. The axis of rotation for that motion is perpendicular to the swing plane and is probably centered at about the sternum of the golfer - *i.e.*, as the swing is driven by the shoulder turn and motion of the arms the club executes a wide sweeping arc. The moment of inertia about that axis is not significant in club design because it is just determined essentially by the mass of the club head and the length of that "radius" - from the sternum to the club head - which is different for different golfers. A second rotation is associated with the hinging and releasing the wrists during the swing. Hence, there will be a moment of inertia associated with that rotation as well. But that is essentially just the mass of the club head (200-225 grams or so) times the square of the length of the shaft (since the wrists will be about at the end of the club's handle). Although not quite the same, it is this MOI that "swing weight" is related to. If you warm up prior to a round with a weighted club, your swing speed is much slower than with your driver on that first tee. Why? Because those two moments of inertia are so much larger with the weighted club than with your driver that it is quite difficult to swing it quickly - which is the point, of course, in using it to warm up and reinforce a slow smooth tempo! So neither of those rotation axes or their related MOI's are particularly interesting to this discussion.



The three rotation axes - and as a consequence, moments of inertia - that are of interest here are associated with the club head itself. One of those is the vertical axis that goes through the center of gravity of the club head when the club is in the proper position to strike the ball. That is the moment of inertia that the USGA regulates with its limit of 5900 g-cm^2 - and the one that is currently a part of golf club manufacturer's design strategies and advertising campaigns. (And for good reason, I might add.) A second axis of rotation that also plays a role in golf club design because it can affect how the golf ball is struck and hence affects the flight of the golf ball is the axis along the shaft itself. Finally, there is a third axis which is horizontal and perpendicular to the target direction (*i.e.,* from the heel to the toe of the driver head) through the center of gravity that also plays a role in how the club interacts with the ball when struck. We will look at all three of those rotation axes and discuss the effects of their moments of inertia.

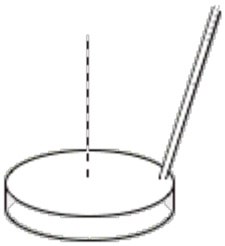
The MOI about the vertical axis through the center of gravity of the club head has the effect or resisting any twisting motion about that axis when a ball is struck off-center, *i.e*., toward the heel or toward the toe of the club and tending to open or close the clubface at impact. That is, if the point of impact is not in line with the center of gravity, a torque is exerted on the club head about that vertical axis which in turn would tend to twist the clubface away from being square with the club head path through the ball. The larger the MOI, the less that off-center hit would affect the orientation of the clubface - *i.e.*, a larger MOI tends to resist the rotation about the vertical axis. A larger MOI should therefore make the club more forgiving on mis-hits - and that is the central issue in the increase in moments of inertia by all the driver manufacturers. It is also the reason for a USGA limit on how large that moment of inertia can be. Surely none of us would want the game to become too easy by having a driver that is so forgiving that every drive would land in the fairway! How boring would that be to have to hit every second shot from the short grass?

But there *is* an interesting side story to this that involves the axis of rotation about the shaft. That is, when you place the driver behind the ball at address, the shaft represents another rotation axis that comes into play during the golf swing. As the club is released through the ball on the through-swing, the club head (as well as the shaft) rotates about that axis in order to square the clubface with respect to the intended target line. The larger the club head, the more the mass of the club head is distributed away from the shaft, hence the larger the moment of inertia of the club head about the axis of the shaft. When the club head design approaches the USGA maximum of 5900 g-cm^2 for the MOI about the vertical axis through the center of gravity of the club head, the moment of inertia about the shaft itself is considerably larger than that - by a factor of two or more, since the shaft is attached near the heel of the club and is thus removed from the center of mass of the club by five centimeters or so (see the figures below). The larger *that* moment of inertia the more difficult it would be to rotate the club head square to the target as the club is released on the through-swing. As a consequence, making the moment of inertia about the vertical axis even larger to make the club more forgiving on mis-hits would have a deleterious effect on closing the clubface - and hence on working the ball from right-to-left (for right-handed golfers). As with most engineering design issues, it is always a compromise!

The third axis of rotation and associated moment of inertia is the horizontal axis parallel to the clubface (or perpendicular to the intended target line) through the center of gravity. At impact, a ball that is struck either higher or lower on the face relative to the center will tend to twist the club head a bit about that axis as well. It can't be much - and it occurs so quickly that one would not think it should have much affect. But the more twisting about that axis that occurs, the more exaggerated the change in ball flight will be. For example, a ball struck high on the club face will tend to twist the head so as to increase the launch angle - sending the ball on a much higher trajectory (and imparting more spin as well which can make it climb even higher). A ball struck low on the clubface will do the opposite - hence reducing the launch angle as well as the spin producing a low drive preventing the ball from achieving the desired trajectory and hence less carry. Both of these effects are deleterious compared to striking the ball near (or just slightly above) the center of the clubface. The higher the moment of inertia about that horizontal axis, the more likely shots hit either above or below the center will mimic the ball flight of a center hit.

The only *regulated* MOI is that about the vertical axis through the center of gravity. An interesting question to ask is why the USGA limit is 5900 g-cm^2? That seems like a very arbitrary number. The units - g-cm^2 - is a result of the definition of moment of inertia, since it depends on the mass (in grams) and the *square* of the distance of that mass from the axis of rotation (cm^2). Although it is not exactly clear why the number is 5900, it is useful to consider a few examples of very simple shapes that could simulate a driver head. Assuming that all drivers are constrained to be no more than 5 inches from heel-to-toe and hence no more than 5 inches from face-to-back, and a driver head is likely to have a total mass of 200-225 grams, it is possible to calculate the moment of inertia about the vertical axis through the center of gravity (or center of mass, a more common expression in physics) for several very simple shapes.

Some moment of inertia examples to consider:



(a) Consider a flat circular disk driver head (I know, it would just slide under the ball - but bear with me here) that has a diameter of five inches (about 12.5 cm) and a mass of 200 grams. It's moment of inertia about the vertical axis through the center of gravity calculates to be about 4000 g-cm^2. A *solid* circular club head of the same mass and radius but with a vertical dimension as well would have the same MOI about the vertical axis through the center of gravity since the distribution of mass parallel to the axis of rotation does not matter in calculating moments of inertia. Of course, one could never hit a ball with it since the "face" would be circular.

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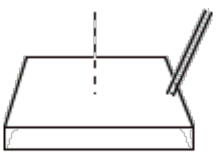
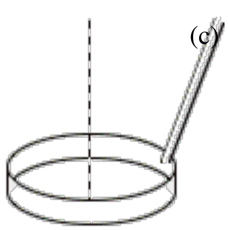


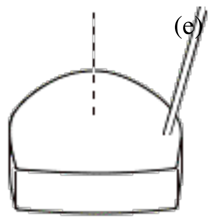
(b) A *square* club head - either a flat plate as above or a solid square club head with the appropriate height to represent a driver - with the same mass and dimensions as the above circular driver would have a larger moment of inertia because some of the mass (the corners) is located farther from the center of mass. It's MOI calculates to be about 5200 g-cm^2 about the vertical axis through the center.

Since modern driver heads are essentially hollow, the moment of inertia calculations are considerably more difficult to do even for simple shapes since some of the mass is distributed (the sole plate and the crown) and some of the mass is around the periphery of the club head in various shapes. That redistribution of mass has the effect of increasing the moment of inertia about the axis through the center of mass compared to the above configurations. How much it changes depends on how the mass is distributed. But making some guesses about how much of the mass would be in the sole plate and crown of the club and how much would be in the bounding sides still allows for an approximate value of MOI to be calculated for the above simple shapes.



(c) For example, imagine if a driver head was circular in shape with *all* of the material equidistant from the CG - that is, consider it to be just be a ring of material without either a top piece or a sole plate with a total mass of 200 g and a radius of 2.5 inches (or, 6.25 cm). It's very artificial, but it is interesting because it is easy to calculate the MOI and shows the upper limit to MOI for a circular shape. The MOI about the vertical axis through the CG would be 8000 g-cm^2 - larger than the flat disk or solid circular driver because all of the mass is located the maximum distance from the axis of rotation rather than being distributed evenly.

(d) If instead of a circular band without top or sole plate as in (a), one made a square band 5 inches on a side - the MOI increases to over 10,000 g-cm^2 because more of the mass is distributed farther from the axis of rotation at the corners of the square shape - hence creating a larger moment of inertia.



But the configuration I found interesting to calculate was a variant of (a) and (c) above. That is, if a sole plate and a crown are included as well as the bounding ring - both circular to enclose the volume of the club head, but constraining the mass to still total 200 grams (assuming half the total mass was associated with the sole plate and crown and the rest was the boundary piece that contained the total volume of the club), the MOI calculates to be 6000 g-cm^2 - the average of the (a) and (b) configurations and just over the USGA limit.

As simple and impractical as that configuration would be as a golf club, it is not difficult to conceive of flattening one side to make a face on the club head and stretching the opposite side of the circle to restore the length of the club head from front to back - and consequently move the CG toward the back of the club. That would make the configuration look a bit more like a driver - and could be done in such a way as to preserve the MOI.

Real club design, of course, is much more complicated than what is presented here with the various choices of materials used, carefully shaped heads, engineered sole plates, varying thicknesses of all the surfaces, imbedded weights to adjust the moment of inertia and location of the center of gravity, and much more. But the ideas - fundamentally - should not be different even though the details are (and are proprietary!). But it is worth noting that small changes can have significant effects. Just changing the distribution of mass to relocate the center of gravity (or *center of mass*, technically) will change the location of the axis about which the MOI is calculated - hence change that value as well. Moving the CG farther back in the club head, for example, will increase the moment of inertia about the axis of the shaft, since it would place mass farther from that rotation axis - and that itself could make it a bit more difficult to square the clubface.

So it is my guess that just creating the general shape of the driver head with a footprint of about 5 inches by 5 inches which completely encloses the 460 cubic centimeter volume of the club head (the current USGA limits), the moment of inertia would fall in the 4000-5000 g-cm^2 range. And the USGA essentially used that upper limit of 5900 g-cm^2 in establishing the regulation in order to still allow some innovation. That is, the goal was to create a standard that left room for a "traditional and customary" shape that conformed to the MOI limit - and also allowed for some variation in shape, engineering, and materials to modify how the mass was distributed as long as the MOI about the center of mass did not exceed that traditional and customary design value. But what the limit does preclude is creating a very large MOI by using very light materials for the general construction then adding enough perimeter weighting - say in the back corners of a square club head to raise the MOI to values much larger than that of a traditional and customary shape.

Of course, it might be the case that the MOI limit just isn't necessary. That is, since further increasing the MOI about the vertical axis through the center of mass to make the club more resistant to twisting on off-center hits

also has the effect of increasing the MOI about the axis of the shaft so that it became ever more difficult to square the clubface on the through-swing, what would be gained in one design parameter - forgiveness - could possibly render the club more difficult to use (especially if a player, for some odd reason, really did want to hit a high draw) due to the added difficulty of squaring the clubface at impact.

And in other clubs? Is it as important a concept?

Does the concept apply *only* to the driver? Of course not. The same principles apply to all golf clubs - and one of the design goals in new golf clubs is optimizing the distribution of mass in the club to accomplish some feature or property the club designer is trying to achieve - whether that means a higher ball flight, a slight draw bias, or just keeping the ball straight once struck even on off-center hits. Does that always involve increasing the moment of inertia? Not necessarily. Golf is a game in which the golfer is trying to control the golf ball. One might think that hitting the ball straight would always be the preferred result (and, for most of us, that is probably about right) - and hence increasing the moment of inertia in every club would be the preferred design goal. But, depending on the skill of the player, controlling the golf ball may well include intentionally turning the ball from left-to-right or right-to-left depending on the circumstances of the shot the player is facing at the time - and that suggests that a high moment of inertia might not always be preferable since it could inhibit the kind of control a good player wants. Hence the wide range of club designs that are currently available. Most players would benefit from just being straight on their tee shots since if that were accomplished every time, it would nearly eliminate out-of-bounds or water hazard penalties or shots from the rough or trees or fairway bunkers - and scores should drop. That suggests high moment of inertia drivers would benefit most golfers. But the skilled player often wants to shape his/her tee shots to avoid hazards, move the ball toward the side of the fairway that gives the best approach to the green, or turn the corner on a dog-leg. So a super-high moment of inertia driver may not be the best choice for that player if that inhibits closing the clubface to hit a controlled draw.

And what about irons and putters? Because the clubhead on irons is much smaller than on a driver - and most of the mass is relatively close to the clubface (again, compared to a driver), the moment of inertia of an iron will be of the order of half that of a driver. But there is a fairly wide range - from less than 2000 to nearly 3000 g-cm^2 for a middle iron. And although most of us can benefit from very "forgiving" irons - clubs with a sufficiently high MOI that when struck off-center, the club does not twist much at impact and the ball still flies fairly straight without too much loss of distance even though mis-hit, the better players want to be able to control the shape of the ball flight - especially with their irons. That is, instead of just hitting the ball toward the green, the good golfer is likely to prefer shaping the ball's flight path toward a back-right pin placement by fading the ball into the right-to-left breeze that might be blowing or perhaps drawing it into a front-left pin position when the green is protected by a deep bunker near that corner of the green. And that explains the large variety of club designs available from forged blade irons hit by many of the touring pros and other elite golfers to the oversized, cavity-back, perimeter weighted, or hybrid iron "game improvement" sets currently on the market for the rest of us. (I've always thought "game-improvement" is not the right term - since *all* players have game improvement as their ultimate goal in choosing the clubs they play.)

The one area that seems to be wide open in clubhead design - and moment of inertia really does have a lot to do with those odd shapes showing up at the course - is in the putter. Since all putts should start out on a straight path perpendicular to the putter face, reducing the twisting of the putter blade when the ball is struck off-center would seem to be a good design feature especially if it also reduced a player's tendancy to rotate the club during the stroke itself. And increasing the moment of inertia about the axis through the center of mass by distributing as much of the mass as possible as far from the center of the clubface as possible seems to be the direction many putter designs are taking. (Some of the current-market mallet-type putters have moments of inertia as high as 4000-5000 g-cm^2.) There are other principles involved as well, of course, in trying to get the ball to roll smoothly as quickly as possible after leaving the putter face, but reducing the tendency of the putter to rotate about its center when the ball is struck should increase the percentage of putts that are directed along the intended line for most golfers. So it is not difficult to see how the idea of increasing the moment of inertia has led to the large and interesting shapes now seen in golf shops as well as on the putting green.

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