Golf Drivers Go the Dis

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On golf courses around the world, plenty of great golf has been played this summer at the professional and amateur levels. Off the links, an ongoing drama relating to golf club performance also has been playing out.

At issue is the performance of golf club drivers. Specifically, golf's ruling bodies have independently determined a rule that sets a uniform, worldwide standard for "spring-like" effect in driving clubs. The organizations will rigorously test golf equipment for conformity to this and the other Rules of Golf.

What this means for equipment manufacturers is that they must develop their products to meet the appropriate standards. What's more, the clubs have to be pleasing in the eyes of the consumers yet be traditional and plain in shape in the eyes of golf's ruling bodies.

One way equipment manufacturers can achieve these goals is through the use of computational analyses, including recent advancements in optimization software and methods. A recent evaluation of a golf driver head demonstrates that using such simulation technology can improve the design, resulting in drivers that are structurally optimized to the performance limit allowed by the Rules of Golf.

Equipped for Excellence

Golf heritage has produced two ruling bodies: the Royal and Ancient Golf Club of St. Andrews (R&A) and the United States Golf Association (USGA). The USGA is, in a way, the younger offspring of the R&A. Formed on December 22, 1894, the USGA is a nonprofit, membership-driven organization that governs the game of golf in North America. Even though Canada has its own golf association, the Royal Canadian Golf Association, it defers to the USGA on many matters. For the most part, the rest of the world is governed by the R&A.

In terms of facilities, the USGA has taken substantial steps to support its equipment standards re-

sponsibilities. A state-of-the-art, 14,000-sq-ft test center was opened in 1984 and is staffed by a cadre of engineers and scientists. The test center studies the whole gambit of golf equipment and devices.

Behind the building is a level, instrumented range onto which golf robots hit shots. In the past, most of the time was spent on testing ball conformation to the rules and publishing a list of acceptable balls. In the mid-1970s, the list fit on one typewritten page; now it is a book of thousands of balls.

The USGA Web site indicates that approximately 20,000 balls are tested each year. Biomechanics sciences are employed to understand how the human aspect of the game is changing. Recent years have shown an increase in driver club head testing and the formation of associated regulations. Today, ball and equipment manufacturers submit their products to the USGA to validate that the equipment conforms to the Rules of Golf.

Why does the USGA make equipment rules? USGA President Reed Mackenzie says for three reasons[1]:

1. The overwhelming majority of golfers believe there should be rules about equipment.

2. Equipment rules have been the responsibility of the USGA for over a century.

3. As an independent ruling body, the USGA has no financial interest and can look out for the good of the game.

Dynamics Rule

The Rules of Golf is a concise and eloquent set of 34 rules. Rule 4 is titled "Clubs," for the obvious reason. Much of this rule has to do with the playing of a round. For instance, how many clubs may a player carry? Fourteen. Further, it states, in general, these clubs shall conform to Appendix II of the Rules.

Appendix II spells out the meaning of USGA conforming clubs regarding shaft straightness, offset, grip, grooves (remember that one?) and a newer criterion known as "coefficient of restitution" (COR). This last criterion is in Appendix II, 4-1e, and is commonly referred to as "4-1e" or "COR." Currently, the USGA limits golf clubs to have a COR less than 0.830.

The concept of COR rests in the engineering realm of rigid body dynamics, the study of how rigid bodies move and accelerate under the actions of forces. The operative word here is "rigid." In the real world, deformation takes place between collid-

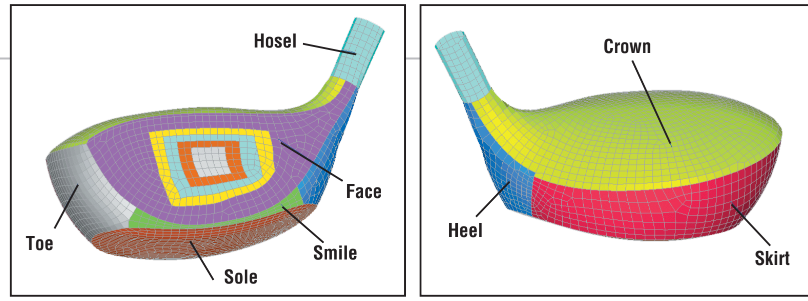
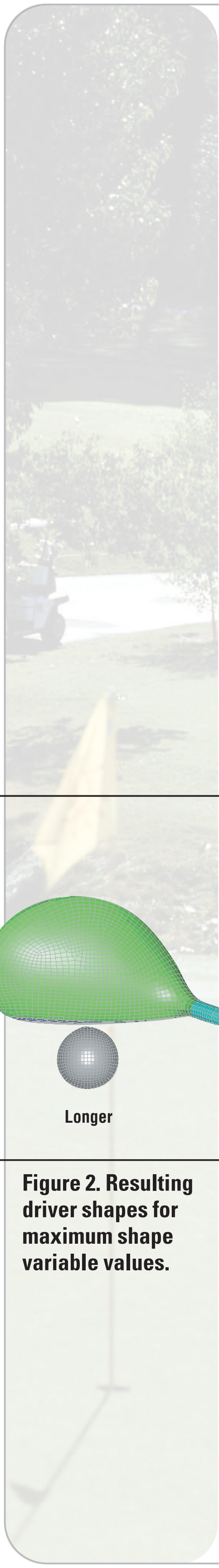


Figure 1. Definitions of regions on the golf club head.

ing bodies, reducing the momentum transferred from one body to another. For example, if the deformation were perfect without energy losses, a ball dropped on the floor would bounce up to its original height. If a ball of artist clay were dropped on the floor, it would deform and stick to the floor. In most impacts, bodies act somewhere between these two extremes.

COR is the parameter used in rigid body dynamics to distinguish between these extremes. For now, consider the ball bouncing off the fixed floor. If a body bounces to the same height from which it was dropped, it has a COR of 1. A body that hits and sticks has a COR of 0. The height a body bounces up is defined by the COR between the two bodies (e.g., ball and floor). When the floor is stationary, a collision having a 0.822 COR value will cause the ball to bounce up 82.2 % of the height from which it is dropped.

When both bodies are moving, the COR definition requires a more precise analysis. Remember, the COR depends on the deformation in both bodies.



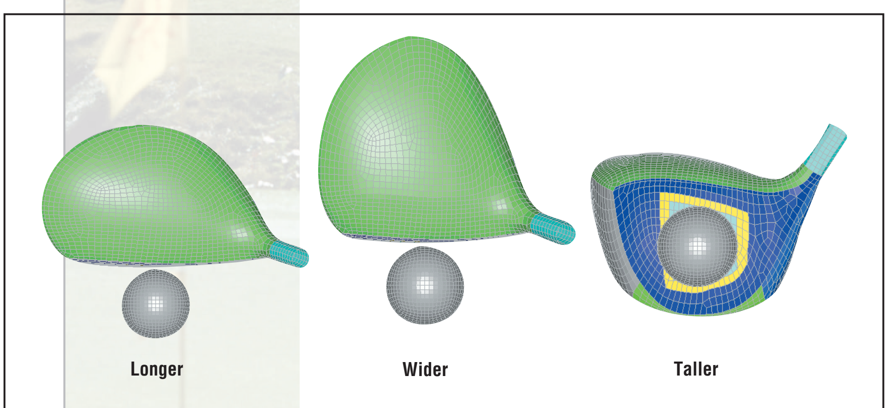


Figure 2. Resulting driver shapes for maximum shape variable values.

Here is the full blown definition of COR: *The COR is the negative ratio of relative post-impact velocities to relative pre-impact velocities*.

What exactly is meant by relative velocities? If two balls move towards one another at 100 mph, the relative velocity is 200 mph. In our simple case from the previous paragraph, one velocity was zero. Hence, the relative velocity is just that of the moving body. Relative velocity reflects the vector nature of velocities.

To measure the COR for a club head and ball collision, the pre- and post-impact velocities for both the club and the ball must be measured. COR is then a simple calculation. As the ball approaches the club, it passes through a pair of ballistic screens measuring the time elapsed to travel a fixed distance. Thus, the inbound velocity is measured. As the ball rebounds, the ballistic screens work the same way in reverse order.

The club head is at rest before impact, so the club head's post-impact velocity is all that's needed to compute the ball-club head COR. Use of physics' conservation of momentum allows for the computation of the COR from the ball's pre- and post-impact velocities. This little trick makes for a more economical experiment, but it also confuses some because the resulting formula has mass terms. Recall the definition of COR is mass-independent.

Here is the bottom line on COR: Increasing COR for a given club head velocity and ball will increase the ball's initial rebound velocity. Thus, the golf shot should travel farther.

Getting to the COR with CAE

Designing golf clubs with a COR of less than 0.830 can be tricky. However, employing simulation software enables manufacturers to evaluate a multitude of designs without having to cast a single part.

One such simulation package is Altair HyperStudy, an open architecture optimization tool that can be used in conjunction with any finite-element solver. Using HyperStudy, with LS-Dyna3D software, our objective was to obtain the maximum possible COR of the club head while maintaining a club head mass of 200 g and keeping club head stress levels below the material yield of 150 ksi.

The optimization problem is defined by the specification of an objective function, constraints and design variables. The model responses that are used for the objective and constraints are limited only to quantities that can be obtained in the solver output. Through the notation convention of HyperStudy, any value in the input deck can be defined as a design variable. Thus, the procedure involved is extremely general.

Structural optimization problems are distinguished by the type of design variables utilized. Generally, size optimization considers the effect of thickness while shape optimization refers to the modification of geometric shape. For a golf driver, which is typically a hollow structure, the key thickness variables are in the face of the club, but the other wall thicknesses also contribute to performance. In optimizing a driver head, both size and shape optimizations should be considered simultaneously.

In our recent CAE study to evaluate the COR for a golf head, three different shape variables were defined: longer in the toe-to-heel sense, wider in the face-to-back sense and taller. (See Figure 1 for golf club head nomenclature.) As part of the evaluation process, the software alters the model slightly without distorting it or affecting the accuracy of the computation. A linear interpolation is used to define the shape variables of all internal nodes lying within the domain. The shape variable changes can be animated to provide visual verification of the vectors and nodes selected. Figure 2 shows the altered shapes of the three shape variables defined in the present study.

In addition to the three shape variables, 10 size variables were defined in the optimization problem. The club face was divided up into five regions in a bulls-eye pattern while the remainder of the club head was divided into five other regions. All regions were defined as optimization variables. The skirt and hosel thickness values were not considered in the optimization problem.

The power of the optimization process can be seen in looking at the objective function as the design variables are perturbed. Figure 3 shows the design variable evolution and the corresponding objective function and constraint evolutions. Here, the COR significantly increases once the response surface has been defined by initial iterations.

One caveat about the simulated optimization results shown here: The ball model used did not have rate-dependent rubber properties. Rate-dependent materials would exhibit damping, which could possibly reduce the COR predicted. To get predictive COR numbers, it is essential to have representative, accurate, validated material properties. However, a major equipment manufacturer recently told me it has measured club heads having COR as high as 0.91.

One final optimization result to point out is that the optimized shape has not radically been altered into something that doesn't look like a golf club head. The combination of shape and size variables has given the program enough design room to greatly enhance COR—resulting in a golf ball that travels farther—while maintaining a good golf head shape.

With the maturity and sophistication of CAE, optimization software can now drive the design process versus its historical role of design evaluation and refinement. As this program demonstrates, robust optimization tools, like HyperStudy, can play a key role in the product development cycle, enabling manufacturers to virtually design, optimize and validate numerous concepts as well as save time and money in the downstream prototype build and test phases. What's more, optimization software can be applied to a range of engineering problems, from golf drivers to space craft, making it a "must-have" tool in manufacturing's arsenal of technological solutions. C2R

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LS-Dyna3D solver technology was developed by and is owned by LSTC. For more information visit www.lstc.com.

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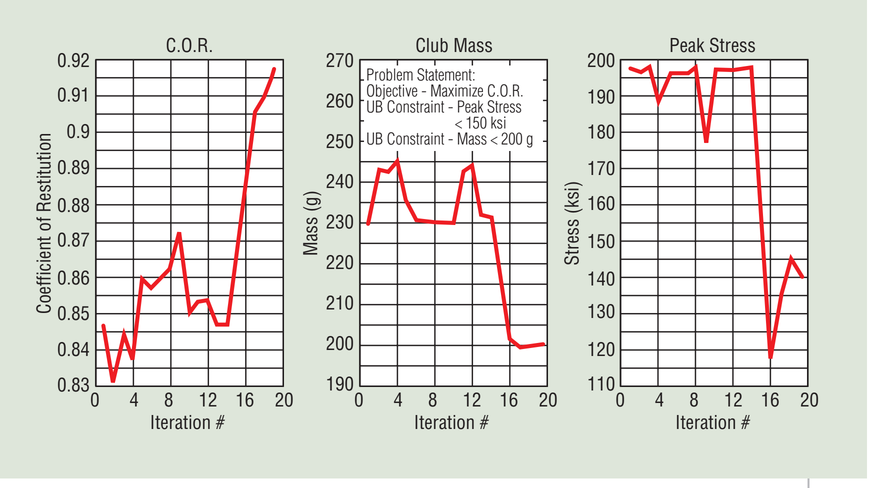
[1] Reference
www.usga.org/about/Perspective/march_april_2002.html

Figure 3. Resulting driver shapes for maximum shape variable values.



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