USGA[1] Rule 4-1e Optimization of a Golf Driver Head Using LS-DYNA and *Altair HyperStudy®*

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ABSTRACT

A simulation of USGA's test procedure for Rule 4-1e was optimized using 3 shape and 10 size design variables. The optimized solution increased the coefficient of restitution from 0.845 to 0.917 while maintaining stresses below 150 ksi and club head mass at 200 g.

Introduction

The advent of titanium golf driver heads has made it possible to make larger hollow structures while satisfying the club head mass constraint. As club head faces became thinner, the United States Golf Association (USGA), which presides over the rules of golf, interpreted Rule 4-1e compliance by defining that the coefficient of restitution (COR) between a known ball (Pinnacle Gold) and the club head cannot exceed 0.829 [1]. The test done to measure this involves a ball projected by an air cannon towards a resting club head without shaft or grip. In general, the clubface is adjusted to be normal to the ball's path and the impact point is the face center. However, the impact point is adjusted to be the point maximizing COR.

In this paper, a generic golf club head model was generated in Unigraphics and meshed using *Altair HyperMesh*®. Different regions of the club head (face, sole, crown, and skirt) were given representative thickness values thus defining the club head's initial mass. Consistent with the USGA's testing, the club head was initially at rest. A ball was given initial velocity into the club head into the center of the clubface. The ball was a two-piece ball modeled with solid elements. Rubber core was modeled using a Mooney-Rivlin material while the cover was taken to be a Surlyn-like elastic-plastic material.

The objective function was to maximize the club-ball coefficient of restitution while maintaining a 200 g club head mass and acceptable club head stress levels. Both shape and size variables were considered in the optimization problem. Shape variables for the head were longer heel-to-toe, deeper front-to-back, and taller top-to-bottom shapes. Size variables included five face, crown, sole, toe, and heel thicknesses. Numerical results show that in 15 to 20 iterations very significant increase in coefficient of restitution are predicted.

Optimization technology using *Altair HyperStudy*® has been utilized to maximize the COR of a generic golf club design subject to design constraints.

USGA Rule 4-1e Model

A generic club head was modelled using Unigraphics. Golf club heads are thin-walled structures having over-all characteristic dimension on the order of 125 *mm* with a range of wall thickness from 0.9 to 2.5 *mm*. *Altair HyperMesh*® was used to create a shell element model of the club head. Standard titanium material properties of the clubhead were represented using the *MAT_PLASTIC_KINEMATIC material property [2]. The club head model was broken into various regions as commonly defined in the golf industry (Fig. 1). These regions are so defined for performance design purposes. For instance, the face thickness is an important parameter in determining the club head's COR. In general, a thinner, larger face will have enhanced COR. However, the face has to remain intact under the influence of thousands of impacts which generate nominal 8.9 *kN* loading. Other sub-components don't have to withstand the impact loads, but their wall thickness is critical for the club head's overall mass. Since a driver was considered in this paper, the mass of the club head must be 200 g. (Actually, the driver is the only club for which COR is critical.) The different region's thickness values are adjusted to accomplish appropriate mass distribution, or, to a lesser extent, sound may be altered by adjusting various region wall thickness.

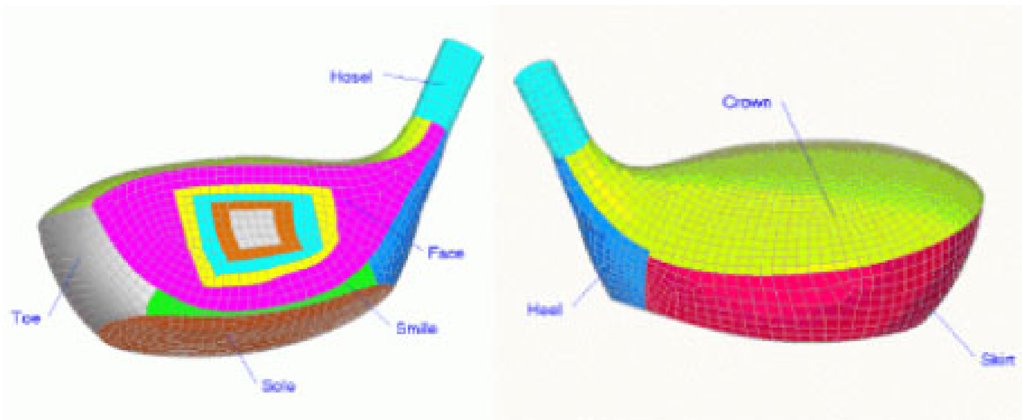

Figure 1 Definitions of regions on the golf club head.

An equally important design criterion is the shape of the club head. The club head has to be pleasing in the eyes of the consumer as well as traditional and plain in shape in the eyes of the USGA. An additional constraint limiting the overall volume of the club head to 460 cm^3 has been proposed and amended in 2001 and 2002, respectively, by the USGA. With all of the preceding in mind, the overall shape is important for the performance and aesthetics of club head design.

A two-piece golf ball model was created in LS-INGRID with solid elements modeling both the cover and core. The rubber core was modeled using the *MAT_MOONEY_RIVLIN_RUBBER material property and the Surlyn®-like cover (that is, neither polyurethane or synthetic balata) was modeled using the *MAT_PLASTIC_KINEMATIC material property. Material properties for these models were determined experimentally.

Consistent with the USGA's test method, the club head (without grip or shaft) starts at rest in the analysis. The ball was given an initial velocity of 55.9 *m/s* (125 *mph*) and impacted into the unconstrained club head. Care was taken to properly align the club head so as to optimize the ball's rebound velocity. The *DEFORMABLE_TO_RIGID_AUTOMATIC option in LS-DYNA was utilized both before and after the contact between the ball and club head to reduce the runtime and facilitate the extraction of the output velocity of the ball using the *rbdout* file from LS-DYNA.

Optimization of COR

Altair HyperStudy® is a generic optimization tool that can be used in conjunction with any finite element solver. 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 gauge while shape optimization refers to the modification of geometric shape. For a golf club, size design variables correspond to wall thickness. In this particular problem, both size and shape optimization have been utilized simultaneously.

Three different shape variables were defined from within the preprocessor: longer in the toe-to-heel sense, wider in the face-to-back sense, and taller. Rhombahedral nodal domains are defined having vectors specified at the vertices which determine the maximum displacement perturbation. A linear interpolation is used to define the shape variables of all internal nodes lying within the domain. The shape variable perturbations can be animated to provide visual verification of the vectors and nodes selected. Figures 2 and 3 show the undeformed and deformed shape of the 3 shape variables defined in the present study.

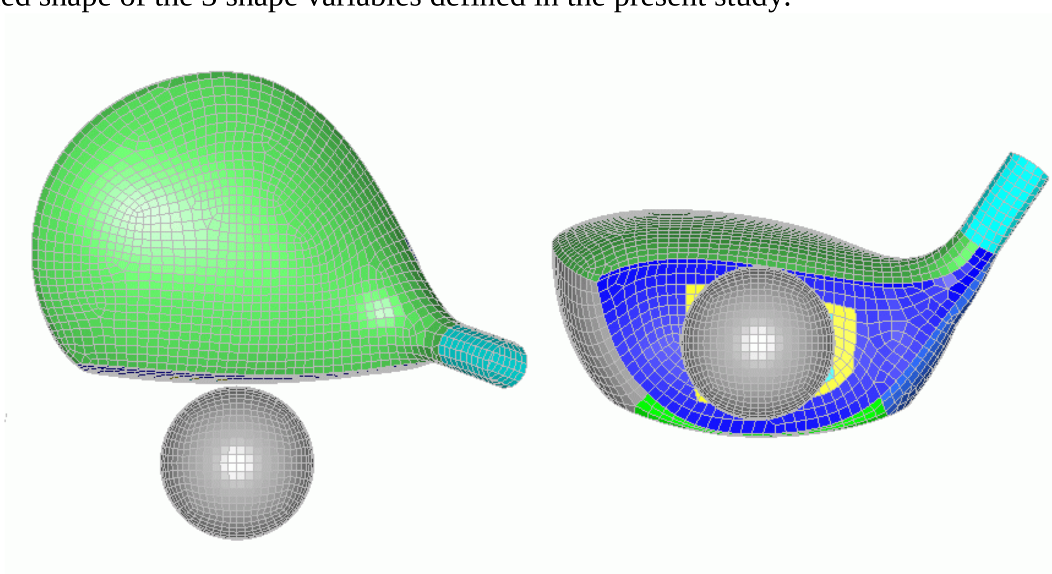

Figure 2 Baseline driver model before shape optimization

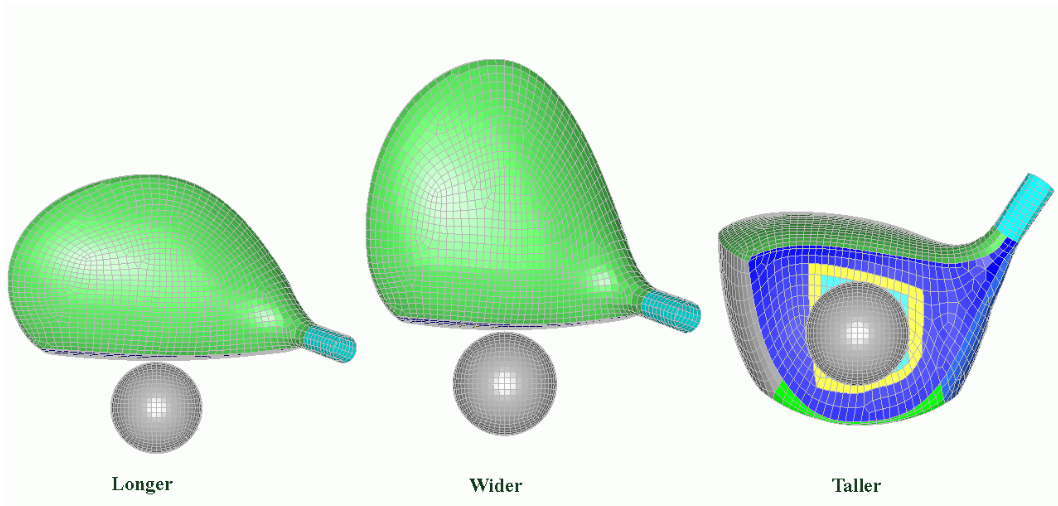

Figure 3 Resulting driver shapes for maximum shape variable value

In addition to the 3 shape variables, 10 size variables were defined in the optimization problem. The club face was divided up into 5 regions in a bulls-eye pattern while the remainder of the club head was divided into five other regions. All of these regions were defined as optimization variables. The skirt and hosel thickness values were not considered in the optimization problem. Table 1 shows the maximum and minimum values for all 13 of the design variables defined.

Design Variable	Initial Value	Lower Value	Upper Value
Longer Shape Variable	0.0	-0.75	0.75
Wider Shape Variable	0.0	-0.75	0.75
Taller Shape Variable	0.0	-0.75	0.75
Face 1 (outer)	0.095	0.04	0.15
Face 2	0.095	0.04	0.15
Face 3	0.095	0.04	0.15
Face 4	0.095	0.04	0.15
Face 5 (inner)	0.095	0.04	0.15
Smile	0.011	0.04	0.15
Crown	0.06	0.04	0.15
Sole	0.10	0.04	0.15
Toe	0.06	0.04	0.15
Heel	0.06	0.04	0.15

Table 1 Shape and size design variable initial values and bounds (all values in inches)

The objective of the optimization problem 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. It is worth noting that the club head's initial mass was taken to be an unrealistic 229 *g*. Rather than manually adjust shell section cards to obtain a proper head mass, it was decided to let the optimization code attain a 200 g head in an optimized manner. Thus, the optimization commences by performing a baseline assessment of the model (using the initial design variable values) and then by performing a series of runs to identify the sensitivity of the responses to each individual design variable. Once the sensitivities are determined, further iterations are performed using various combinations of design variables until a converged solution is reached. Further theoretical background and a comparison of the various techniques to achieve the optimum solution are found in the literature [1,2]

Optimization Results

HyperStudy® obtained a converged solution for this optimization problem after 19 iterations. Figures 4 and 5 show plots of the design variables and model responses at each iteration of the run. It can be seen from these plots that the COR is increased by approximately 9 percent while meeting the 200 *g* mass constraint and keeping the club head stresses below the yield value of 150 *ksi*.

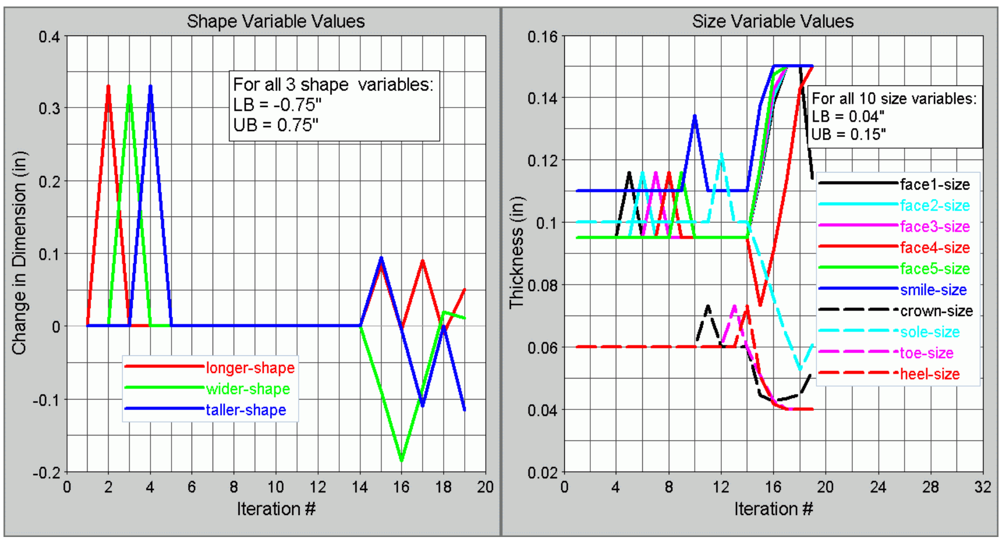

Figure 4 Design variable evolution throughout optimization

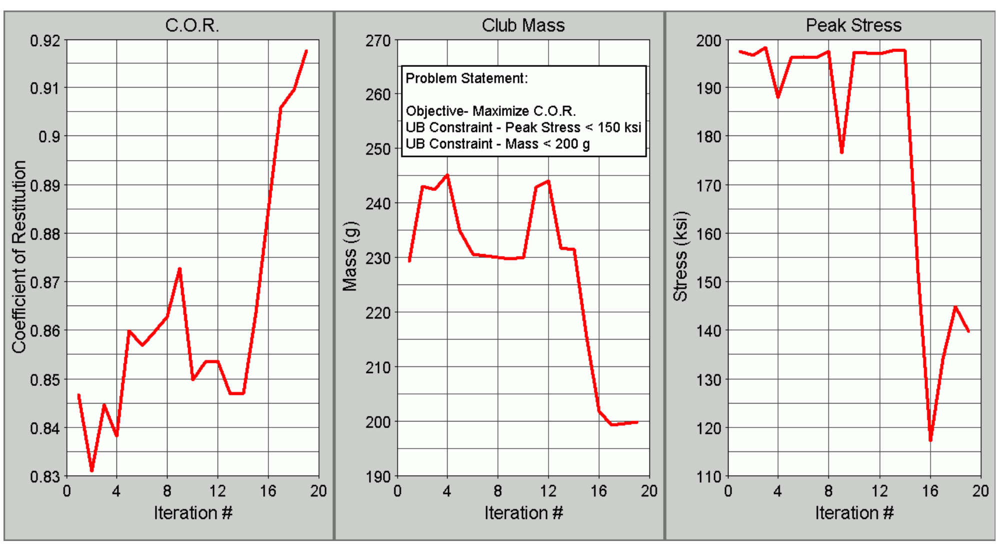

Figure 5 Objective function and constraint variable evolutions

Table 2 shows the value for each design variable in the converged solution. The cross-section of the club head before and after optimization is shown in Figure 6.

Design Variable	Final Value
Longer Shape Variable	0.05”
Wider Shape Variable	0.01”
Taller Shape Variable	-0.12”
Face 1 (outer)	0.114”
Face 2	0.15”
Face 3	0.15”
Face 4	0.15”
Face 5 (inner)	0.15”
Smile	0.15”
Crown	0.052”
Sole	0.061”
Toe	0.040”
Heel	0.040”

Table 2 Finishing design variable values

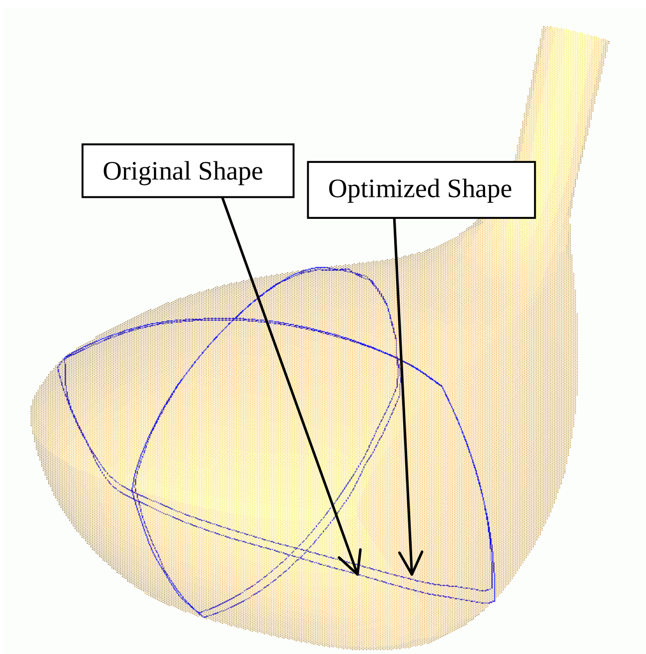

Figure 6 Graphical representation of initial and optimized cross-sections

Conclusions

Structural optimization was used to increase the coefficient of restitution of a titanium driver from 0.845 to 0.917. The final optimized shape is not unreasonably distorted even though the maximum perturbed shapes are not acceptable aesthetically. The optimization converged in 19 iterations making the process affordable in terms of computation costs.

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