OPTIMISATION OF KNEE BOLSTER LOADING
FOR EURO AND US NCAP

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Abstract: The application of optimization technology to crashworthiness design is a rapidly evolving discipline. This paper details the application of optimization techniques to automatically determine the most efficient knee bolster configuration. Altair StudyWizard provides an optimization toolkit to vary specified design variables (i.e. shape, size and stiffness) to maximise the internal energy absorption of the system. The crashworthiness code, LS-DYNA, is used to obtain the system response data. The technology demonstrates how the geometry of knee bolster can evolve a simple strut configuration into a curved expanded geometry. Once an analysis methodology has been pioneered the optimization studies can be routinely applied to produce a 25% improvement on a baseline design.

Keywords: Optimisation, Crashworthiness, LS-DYNA, HyperOpt

1.0 INTRODUCTION

The competitive nature of the automotive industry demands continual innovation to enable significant reductions in the design cycle time while satisfying ever increasing design functionality requirements (e.g. minimising mass, maximising stiffness etc). Optimization technology provides a scientific approach to automatically determine the most efficient design within competitive time constraints.

The application of optimization technology to crashworthiness and occupant protection assessments is a rapidly evolving discipline [1-3]. This study applies optimization to automatically determine the most efficient configuration for a knee bolster system. Thus providing a powerful visual example of the technologies capabilities.

The Altair StudyWizard [4], which contains a Design of Experiments (DoE) engine and sequential response surface technology, Altair HyperOpt [5], provides a powerful toolbox to automatically optimise highly dynamic non-linear systems. The dynamic finite element analysis code LS-DYNA [6] was used to compute the response of the system to various design inputs.
The objective of the study was to automatically vary various design variables to optimize the energy absorbing characteristics of the system whilst satisfying various force limiting constraints. The main focus was to allow the optimization technology to automatically change the geometry of the knee bolster, which is the system’s primary energy absorption component.

The optimization study has been carried out on a sub-system model of the knee bolster (Figure 1b). Load requirements were obtained from initial concept models of European and Federal front impacts (Figure 1a), and final verification was carried out using full occupant / interior model simulations using LS-DYNA3D (Figure 1c).

2.0 OPTIMIZATION SET-UP

2.1 Baseline Response

The baseline knee bolster system consists of an Instrument Panel (IP) substrate, polyurethane backing foam, a diamond knee bolster configuration and a rigid backing plate, which is impacted by a rigid knee form (Figure 2).
The knee bolster will be manufactured from extruded aluminum and consequently the section geometry does not vary along the structure’s width. A fixed design requirement is the distance between the backing plate and the IP substrate.

A non-linear material response was specified for the aluminum knee bolster and the polyurethane backing foam was characterised by a pressure / compressibility curve. The boundary conditions consist of a totally fixed backing plate and contact conditions specified between the various components.

The impact loading event was simulated by applying a constant velocity to the knee form throughout the duration of the analysis. This ensures that the dynamic compliance of the system was sampled throughout the complete stroke of the intrusion. The intrusion stroke was defined as the distance between the IP substrate and the rigid backing plate.

![Figure 3: Schematic Knee Bolster Force / Displacement Characteristic](image)

The primary design signature of the system is the knee form impactor force versus knee form displacement response. This force was required to remain within specified design load limits.

The deformation characteristics of the baseline knee bolster model can be broken into three phases (Figure 3). The first phase of the crush (A) was the deformation of the polyurethane foam. The knee bolster collapses (B), with the structure bottoming out (C).

2.2 Optimization Set-Up

Objective

The StudyWizard is extremely flexible, any result type computed by LS-DYNA can be identified as an objective to maximise or minimise. Common objective variables for crashworthiness optimization studies are the minimisation of mass or the maximisation of internal energy.

An efficient knee bolster system would not only satisfy the force limits but also maximise the internal energy of the system. This requires matching the systems response to the design.
knee bolster force / displacement curve. Since the area under this curve directly relates to the internal energy absorbed by the system.

By selecting internal energy as the objective, the system consistently absorbs energy throughout the event. Consequently, the system will dynamically resist the impact, avoiding the higher forces encountered at the large intrusion stroke displacements.

**Constraint**

The knee bolster force must not exceed a lower force constraint, specified by European Legislation (Fe) and an upper force constraint, specified by US Federal Legislation (Ff) up to a maximum intrusion stroke ($\delta$). This maximum stroke value was considered as a realistic limit for the system to achieve. Consequently, two force constraints are defined within the respective displacement windows (Figure 4).

![Figure 4: Design Knee Bolster Force Versus Displacement](image)

**Design Variables**

The design variables have been divided into two categories. The first consists of constantly selected design variables, which are specified, in all optimization studies performed. These consist of foam thickness and foam density. The density of the foam defines the grade of polyurethane and the resulting stiffness characteristics.

The second category is the shape variables used to define the knee bolster geometry, which is confined within the defined package space (Figure 5). The objective is to automatically develop a geometry within the design space to produce the most efficient energy absorption component.
3.0 OPTIMIZATION STUDIES

3.1 Introduction

This section details the optimization studies performed on the knee bolster system. The StudyWizard [4] was used to construct a response surface from which a sequential optimization procedure was performed using HyperOpt [5]. This code inputs the computed values of the constraints and the objective and determines the new design variable values. Each design iteration requires LS-DYNA [6] to be executed.

A series of optimization studies are performed where the complexity of the design variables used to define the knee bolster geometry within the package space was gradually increased.

A limitation of the technique was that the geometry could only evolve using the initial starting nodes. Consequently, new elements representing new structure cannot be added during the process. However, complex shape perturbations can be specified to the initial starting nodes using HyperMesh [7], which contains the specialist tool AutoDv [8].

3.2 Single System

Diamond

The design variables consist of foam density, foam thickness and different thickness values for the front and rear of the knee bolster. The initial starting configuration consists of a diamond geometry, which provides a reference solution to the baseline assessment (section 2.1). Three independent linear shape variables are applied to the starting configuration to control...
the evolution of the geometry. Consequently, a total of seven design variables have been defined.

The optimized values of the design variables show that the most significant changes are to the material thickness and foam stiffness. This indicates that the knee bolster geometry of the baseline design was close to the optimum for the design variables chosen.

The baseline design model violates the upper force constraint. The optimized design automatically varies the design variables to satisfy the constraints (Figure 6).

![Figure 6: Force / Displacement Characteristic of a Single System](image)

Comparison of the optimized diamond solution with the baseline response shows that the most significant change is the controlling of the peak force up to the maximum intrusion. This shows how the optimization has successfully achieved the design constraints. The energy absorption of the knee bolster was increased by 13% in comparison with the baseline.

**Single Strut**

The single strut example provides a powerful visual demonstration of optimization technology. This simplistic starting configuration (Figure 7a) must significantly modify the knee bolster geometry to achieve an optimized solution.

The shape variables applied to the knee bolster consist of both linear and harmonic shape variables. The HyperMesh tool, AutoDv, has the facility to specify a family of harmonic functions [9] which can be superimposed to allow increased generality of the evolved geometry.

The final optimized geometry of the knee bolster (Figure 7b) has evolved into a curved configuration whose height was similar to the previously optimized diamond. This was further emphasized by an almost identical force versus displacement response (Figure 6). The energy absorption of the knee bolster was increased by 15% in comparison with the baseline.
3.3 Dual Systems

Diamond with a Tie

The optimization technology can only introduce physical characteristics into a system, which are inherent in the combination of starting configuration and the specification of the design variables. Consequently, a starting configuration, which consists of the initial diamond with a center tie (Figure 8a), will introduce important physical mechanisms.

Typically, a center tie allows the two sides of the knee bolster to crush independently at different loads and also increases the geometric stiffness of the structure. This increase in the geometric stiffness can produce a reduction in material thickness and consequently a decrease in the mass of the system. Additional flexibility was achieved by defining two harmonic shape variables to the inclined faces of the knee bolster design. This effectively allows a curvature to be introduced into the faces of the structure, facilitating a progressive crush characteristic.
The final optimized geometry (Figure 8b) has evolved into a doubly curved section design. The force versus displacement response (Figure 9) exhibits a two stage crush characteristic. The two discrete force limits, which define the constraint, indicate the maximum internal energy will be achieved by a structure, which exhibits a two stage characteristic, which satisfies each force limit.

The optimized solution satisfies the constraints, however the system exhibits poor energy absorbing characteristics. The optimum design produces a total internal energy, which was below the previously optimized diamond configuration. This was due to the systems difficulty in satisfying the second force constraint which was violated as the maximum intrusion was approached.

To demonstrate the merits of this design, a second optimization study was performed with the maximum intrusion stroke relaxed by 10 mm. The optimized design (Figure 8c) has evolved the configuration into a doubly curved section design. The force versus displacement characteristic (Figure 9) exhibits a well defined two stage crush response that results in a more efficient design.

This optimized design has increased the total internal energy by 17% compared to the baseline diamond solution. By reducing the severity of the second force constraint the optimization has significantly improve the design. This highlights the sensitivity of the solution to the maximum intrusion stroke.

**Assymetric Cells**

All previous studies have applied symmetric shape variables which ensures the optimization technology produces a shock absorber geometry which is symmetric about a mid-plane located along the absorbers length. The flexibility of the system can be increased by specifying asymmetric shape variables which can independently vary a dual cell system.

The optimum design shows that the two cells have developed into different geometric forms. The front section has formed into a curved form, whilst the rear has remained as a diamond, but has developed into a higher center height.
The force versus displacement characteristic (Figure 10) shows that the optimization has successfully generated a design that provides a clear two-stage crush characteristic, whilst requiring no relaxation of the maximum intrusion stroke. As a result, the total internal energy is increased by 24% compared to the baseline solution.

3.4 Discussion of Results

A summary of the normalised total internal energy and the normalised mass of the configurations studied are presented (Table 1). The baseline assessment has been used to normalised the values produced by the optimization studies.

<table>
<thead>
<tr>
<th>Optimisation Study</th>
<th>Total Internal Energy (%)</th>
<th>Component Mass (%)</th>
<th>No. Design Variables</th>
<th>Total No. of Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>13</td>
<td>-2.4</td>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>Single Strut</td>
<td>15</td>
<td>-7.1</td>
<td>7</td>
<td>39</td>
</tr>
<tr>
<td>Center Tie</td>
<td>17</td>
<td>-4.8</td>
<td>7</td>
<td>34</td>
</tr>
<tr>
<td>Double Diamond</td>
<td>25</td>
<td>-2.4</td>
<td>6</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 1: Summary of Optimization Studies

For the baseline diamond configuration, the technology automatically improved this design by satisfying the constraints and improving the energy absorbing characteristics. The optimized diamond configuration had the flexibility to significantly modify the starting geometry; however, the geometric design variables exhibited only small variations.
The single strut demonstrates the advantages of this technology within the design process. This simple starting configuration was combined with complex shape variables. The structure evolved into a curved geometry with a height similar to the previous study.

Two dual cell systems were considered with the shape variables allowing for a symmetric and asymmetric geometry of the cells to evolve. Both these systems exhibited a two stage response required to maximise the energy under the two discrete force limits.

As exhibited by the diamond with the center tie, the constraints can be easily violated since throughout the dynamic event the knee bolster force can exhibit localized spikes. The problem could be re-formulated to attempt to least square curve fit the constraint or define a continuous function for the constraint.

4.0 CONCLUSIONS

The application of the StudyWizard and HyperOpt to produced optimum knee bolster systems has been demonstrate. An initial methodology of how this technology can be used to achieve the force limits while achieving the objective of maximising internal energy has been pioneered.

The optimization problem set-up is fundamental to successful application. The system cannot achieve the objective of a true global optimum, if the combination of the starting configuration and the design variables do not exercise particular structural mechanisms. It is a physical impossibility to achieve certain response if the system has not been allocated certain characteristics.

The simple single strut starting configuration combined with the complex shape perturbation variables demonstrates the power of the technology. Since the geometry was automatically evolved to an optimum single system design. Experience obtained on this study can increase the predictive capabilities of the technology. Additional constraints and different design variables can be formulated to further increase the predictive power of the technology.

Once the methodology has been established, it can be routinely applied to the systems containing the connecting tied structural element. The technology can have a significant impact on the design cycle time. The resource requirements are focused onto the computer and away from the engineer.

5.0 REFERENCES


