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Product Standardization using Axiomatic Design

Raviraj U. Nayak
Email raviraj.nayak@gm.com
General Motors Corporation
6600 East 12 Mile Road
M/C 480-400-111
Warren, Michigan 48092

Kee H. Im
Email kee.im@gm.com
General Motors Corporation
6600 East 12 Mile Road
M/C 480-400-111
Warren, Michigan 48092

ABSTRACT

Axiomatic design represents a scientific approach for the synthesis and analysis of product design. In this paper, we present an application of axiomatic design approach for product standardization, using the independence axiom. The automotive bumper system is chosen as a case study. The amount of energy absorbed by bumper beam and energy absorbing material (foam) during a 5mph impact are the defining characteristics of bumper system. The two functional requirements that the bumper system design should satisfy are:

1. The force at the bumper/rail attachment point at maximum deflection should be less than the capacity of the rail.
2. The design also should restrict the deflection of the bumper beam (measured by the beam stroke and system stroke) to be smaller than the distance to the nearest damageable component such as the headlights, radiator etc.

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The design parameters for a bumper system are the vehicle rail spacing, vehicle mass, sweep radius of the bumper beam, beam material, type of beam section, beam width, height, and thickness of the section.

Since there are a lot more design parameters against two functional requirements, the system is redundant causing multiple couplings between the functional requirements. A change in any one of the design parameters causes a change in both the rail force and the deflection. Satisfying either one of the functional requirements, involves doing a number of iterations to determine the dimensions of the design parameters related to the bumper beam. Engineers have to spend a lot of time to figure out the right combination of parameters for every vehicle.

This paper demonstrates how the independence axiom can be used to manage the complexity of the system, by minimizing the coupling between the functional requirements. The dimensions of the additional design parameters related to the bumper beam are standardized. Once we design a system with low coupling it is easy to satisfy the functional requirements with a few

tuning parameters. This methodology could be potentially extended for standardization of other products.

1 Introduction

In the past decade the automotive industry has seen fierce global competition for market share. There have been many mergers in which the partners have sought to fill the gaps in their portfolio and market presence. The mergers attempted to harness the individual partner's dominance in a segment of the market, or a field of technology, for the benefit of the merged entity. It is in this context that the idea of product standardization gains great importance.

Product design is more complex today than ever before, because the manufacturer needs to sufficiently differentiate the products being offered to satisfy a diverse market. However the manufacturer also needs to increase the level of integration between the products to reduce costs. This is especially true for today's automotive industries. One way of doing this is to concentrate the design efforts at the level of the product family and on the development of product platforms that represent the key components and assets that are the common core of products of the family (Meyer and Utterback 1993).

In this paper, we have demonstrated how principles of axiomatic design can be used to design a good product platform. We have applied these principles to design a family of automotive bumper beams. A description of the bumper system in terms of the design requirements and parameters is given in the next section. In the following sections, the methodology of using axiomatic design principles to design a family of bumper beams is discussed. In the concluding section, we have discussed the possibility of using this methodology for designing product families in general.

2 Automotive bumper system

In the automobile, the bumper beam serves to protect the damageable components such as the radiator, the headlights etc., in the event of a low speed crash. As shown in Figure 1, the beam is attached to the vehicle rails. The spacing between the rails is decided by the vehicle design and the bumper system designer has little control in this process. Similarly the mass of the vehicle is a given to the bumper system designer. The amount of curvature or sweep of the beam is governed by the styling of the vehicle. For example, sports cars tend to have a larger curvature or small sweep, whereas at the other extreme is the flat bumper beam, such as used in early vehicles. In most vehicles, the bumper beam is located behind the front fascia. The space between the fascia and the bumper beam is filled with an energy absorbing material.

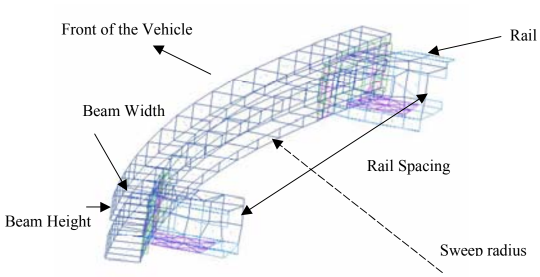

Figure 1. Vehicle Bumper System

The design of the bumper system involves the design of the bumper beam section, in terms of the type of section, material, width, height, and thickness of the section. There are standard types of bumper beam sections, generally developed by bumper beam suppliers. These section types are proprietary and have certain defining parameters such as its width, height and thickness. Thus the design parameters that affect the bumper performance fall in to two categories: those that are given to the bumper designer from the vehicle design such as rail spacing, mass, and sweep of the beam, and those that are determined by the bumper designer such as section type, material, width, height, and thickness.

The bumper beam is designed such that the deflection of the beam in the event of a low speed crash is less than the distance to the first damageable component. The stiffness of the beam should be such that the force at the rail should be less than the load carrying capacity of the rail. This ensures that the rails are not damaged in a low speed crash. Thus, the deflection and the force are two functional requirements of the bumper beam. Bumper system designers often have to look at deflections of the beam at different locations. They also have to design the energy absorbing foam since the bumper system performance is affected by the selection of the energy absorbing foam. There are also various statutory requirements and tests that validate a bumper system in terms of its performance in a low speed impact. These regulations differ from country to country. It needs to be clarified that the bumper design discussed in this paper is a generalization of the design problem. Since the objective of this paper is to discuss the product family design method, the federal regulations and test details are skipped in this paper. We have also not considered the energy absorbing foam here. The design method discussed here can be easily extended to include these details.

1. Axiomatic design and product family design methodology

Axiomatic design classifies the design in terms of the independence between the functional requirements and also in terms of the independence amongst the design parameters. As a first step, we identify the functional requirements and design parameters of the bumper system and build a design matrix. We then identify the design that results in maximum independence of the functional requirements. Once this is done we can satisfy new functional requirements by changing only its corresponding design parameters. In this way, we can design a family of bumpers that meet a wide range of requirements. We achieve standardization because all the bumpers of the family are derived from the same original design. The above is the simple outline of the methodology for product standardization. However there are certain challenges that need to be addressed which are discussed below.

Bumper FRs and DPs

The bumper system has to meet the force and deflection requirements discussed earlier. Hence there are two FR's. As discussed earlier the design parameters fall in to two categories. Those design parameters that satisfy vehicle level requirements such as sweep, mass, and rail spacing are not controlled by the bumper designer and have to be satisfied. At the same time these design parameters affect the bumper performance, we therefore put these three design parameters under both the FRs and DPs. If we look at the design parameters of the bumper that are controlled by the bumper designer, they are the section type, material, section width, height, thickness, foam density and thickness. In this paper, we will demonstrate the methodology for a given section type and material without foam or any other energy absorbing material. Thus the final design matrix is as shown in Figure 2.

The design matrix shows that the bumper system is a redundant and highly coupled design. With the current technology, it is unlikely that there will be an innovative bumper system with uncoupled or a decoupled design matrix. That is why we have to do optimization to identify the design with maximum independence as measured by the reangularity and semangularity metrics.

$$\begin{bmatrix} \text{Force} \\ \text{Deflection} \\ \text{Sweep} \\ \text{Rail Spacing} \\ \text{Mass} \end{bmatrix} = \begin{bmatrix} X & X & X & X & X & X \\ X & X & X & X & X & X \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \text{Section Height (h} \\ \text{Section Thicknes} \\ \text{Sweep (s)} \\ \text{Rail Spacing (r)} \\ \text{Mass (m)} \\ \text{Section Width (w} \end{bmatrix}$$

Figure 2. Design matrix for bumper system

Identifying design with maximum independence

It is essential to find out the transfer function to actually calculate the independence using reangularity (R) and semagularity (S). It is not trivial to establish the closed form transfer functions such as,

$$\text{Force} = f_1(\text{h,t,s,r,m,w})$$

$$\text{Deflection} = f_2(\text{h,t,s,r,m,w}).$$

We, therefore, developed response surface models to predict the force and deflection response of the bumper system represented in Figure 2. This response surface model is a surrogate model of the actual LS-DYNA simulation. With the response surface model, we can rapidly estimate the performance of a design with decent accuracy. This is very useful when we explore the design space for alternatives that maximizes the reangularity (R) and semangularity (S) measures.

For designing the product family we identify the point in the design space where the terms coupling the rail spacing, sweep, mass and the force, deflection of the beam are minimum. We formulate an optimization problem to find the point of maximum R and S. The objective is to find the bumper design parameters such as the Section Height, Section Width, and thickness such that it results in design where the functional requirements have the smallest coupling due to the design parameters related to the vehicle design such as Sweep, Rail spacing and Mass. The square 5x5 matrix is used to calculate the R and S. The column related to the Section Width is dropped from the calculation since we propose to hold the Section width fixed at a value.

The range of rail capacity and the allowable deflections of vehicles of the targeted family of vehicles, for which the bumper family is being designed, are represented as distributions. The objective of the optimization is to maximize the R and S subject to the constraint that the force and deflection are below the mean values of the distributions of allowable rail capacities and deflections. After the point of maximum R and S are found the additional design parameters related to the bumper system such as the Section Width type and material are fixed. These additional design parameters become the product family platform i.e. they are held fixed for all the products of the family.

2 Designing the product family

Once we identify the product platform we can then develop the product family to satisfy a range of requirements. The independence obtained in the previous section holds true in the window around the point of maximum independence for which the design is linear. If the design is highly non-linear and the sensitivities of the FRs to the DPs change the independence does not hold true. The trick is to figure what is the widest window for the product platform.

In our bumper case, we have to find what is the widest range of rail spacing, sweep, and mass over which the beam could be used with modifications of height and thickness to satisfy the force capacity and deflection limits of the particular vehicle. To find the maximum window, we have to formulate a new optimization problem. The goal of the optimization is to maximize the width of the range of rail spacing, sweep, and mass, subject to the constraints on the force and deflection. In the optimization, we allow the thickness and the width of the beam to vary within a feasible range. To simplify the problem, we assume uniform distribution for thickness and width. The range of rail spacing, mass, and sweep are also represented by uniform distribution, since we have to assume that there is an equal probability that the designer could decide on any sweep value, or that the vehicle could have any rail spacing or mass. We use Monte Carlo simulation method to find the response distribution for a range of input distribution of mass, sweep, rail-spacing thickness and height. The response distributions are subject to constraints of the force and deflection. The solution has to meet the constraints on the force and deflection.

To put it simply, if we are able to find the ideal solution where the R and S of the design matrix shown in the Figure

2 are 1.0, then we can use the same beam type, material, and width, for vehicles with different rail spacing, sweep, and mass of the vehicle within the window where the independence holds good. We just have to adjust the beam height and thickness to satisfy the force capacity and deflection limits of each vehicle.

3 Conclusion

In the above we included Section height and thickness to correspond to the two functional requirements and section width was considered as an additional design parameter. This choice of section-width, as an additional design parameter is arbitrary. We could suitably formulate the optimization problem to determine what design parameter best correspond to the functional requirements that results in a design that has maximum independence.

The methodology discussed in this paper designs a product family based on the principle of maximizing the independence of functional requirements. When a design is developed that has maximum independence amongst the different functional requirements we can change the FR for a particular product by changing its corresponding DP with out affecting the other FRs. Also since only a few DPs need to be changed to satisfy the different requirements there is essential standardization, which lowers the cost of providing variety.

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