Available online at www.sciencedirect.com

ScienceDirect

Journal of Magnesium and Alloys 2 (2014) 99−108
www.elsevier.com/journals/journal-of-magnesium-and-alloys/2213-9567

Full length article

Design of lightweight magnesium car body structure under crash and vibration constraints

Morteza Kiani [a], Imtiaz Gandikota [b], Masoud Rais-Rohani [b,c,*], Keiichi Motoyama [b]

[a] *Engineering Technology Associates Inc. (ETA), MI 48084, USA*
[b] *Center for Advanced Vehicular Systems, Mississippi State University, MS 39762, USA*
[c] *Department of Aerospace Engineering, Mississippi State University, MS 39762, USA*

Received 10 March 2014; accepted 29 May 2014
Available online 17 July 2014

Abstract

Car body design in view of structural performance and lightweighting is a challenging task due to all the performance targets that must be satisfied such as vehicle safety and ride quality. In this paper, material replacement along with multidisciplinary design optimization strategy is proposed to develop a lightweight car body structure that satisfies the crash and vibration criteria while minimizing weight. Through finite element simulations, full frontal, offset frontal, and side crashes of a full car model are evaluated for peak acceleration, intrusion distance, and the internal energy absorbed by the structural parts. In addition, the first three fundamental natural frequencies are combined with the crash metrics to form the design constraints. The wall thicknesses of twenty-two parts are considered as the design variables. Latin Hypercube Sampling is used to sample the design space, while Radial Basis Function methodology is used to develop surrogate models for the selected crash responses at multiple sites as well as the first three fundamental natural frequencies. A nonlinear surrogate-based optimization problem is formulated for mass minimization under crash and vibration constraints. Using Sequential Quadratic Programming, the design optimization problem is solved with the results verified by finite element simulations. The performance of the optimum design with magnesium parts shows significant weight reduction and better performance compared to the baseline design.

Keywords: Multidisciplinary design optimization; Magnesium structure; Car body structure; Crashworthiness; Vibration; Vehicle design

1. Introduction

With the growing industrial development and reliance on fossil fuels, Green House Gas (GHG) emission has become a major problem. There are many sources for GHG including the emissions from passenger cars with internal combustion engines. In the United States, the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) issued a joint regulation in August 2012 [1]. This new regulation will be imposed on passenger cars in model year 2017 through 2025 to improve GHG and fuel consumption standards for cars. Based on this new regulation, the emission for combined cars and trucks has to be reduced from 243 g/mile in 2017 to 163 g/mile in 2025; moreover, the fuel economy must be improved from 36.6 mpg in 2017 to 54.5 mpg in 2025. However, carmakers have to design their products not only to fulfill the new regulations but also to remain in competition with peers. Regardless of different successful approaches to improve fuel economy such as fuel quality enhancement, development of high performance engines and

---

[*] Corresponding author. Present address: Bagley College of Engineering, P.O. Box 9544, Mississippi State, MS 39762, USA. Tel.: +1 662 325 2270; fax: +1 662 325 8573.

E-mail address: masoud@ae.msstate.edu (M. Rais-Rohani).

Peer review under responsibility of National Engineering Research Center for Magnesium Alloys of China, Chongqing University

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jma.2014.05.005.

fuel injection system, weight reduction is one of the promising approaches as by 10% weight reduction in passenger cars, the fuel economy improves by as much as 6–8% [2].

Applications of lightweight materials not only bring the potential for carmakers to reduce the car weight but also simultaneously satisfy the new regulations of fuel economy and emissions. A few lightweight materials have been introduced in automotive industry such as aluminum, magnesium, and composite materials. According to Dieringa and Kainer et al. [3], magnesium is considered to be a frontrunner material among other lightweight materials. A magnesium car body structure with equal stiffness can be 60% or 20% lighter than steel or aluminum design, respectively [4]. According to Refs. [5,6], the average use of magnesium in cars has increased from 0.1% (1.8 kg) in 1995 to 0.2% (4.5 kg) in 2007 in the United States. The future vision for magnesium shows the use of this material in cars will increase by 15% (about 227 kg) by 2020 [7]. This study estimates 5.5 kg of average use of magnesium in the current body structure for the cars produced in the United States. This small application of magnesium shows the concerns of the carmakers about magnesium related challenges. Some of these challenges have been addressed in the USAMP's report such as cost effectiveness, poor corrosion, joining, and durability.

Prior works on the application of magnesium alloys in car body structure include Parrish et al. [8] where 22 steel parts were replaced with magnesium (AZ31) counterparts. This replacement combined with structural optimization saved 54.5 kg in weight while most of the crashworthiness characteristics of the new design remained similar to the baseline design. Logan et al. [9] show that magnesium body structure not only offers more than 40% weight reduction as compared to a conventional steel structure but it also significantly improves the structural performance.

In extending the prior research by Parrish et al. [8], this paper investigates weight reduction of a car by combining multidisciplinary design optimization and replacing the baseline steel with magnesium counterparts so that the crashworthiness and vibration characteristics of the new design can be improved or at least maintained similar to its baseline design. The design optimization is based on minimizing the mass as the objective function. In addition, the peak acceleration, intrusion distance, energy absorption, and the three fundamental frequencies are selected as the design constraints. The crash simulations are set up only for a subset of crash scenarios typically used in the automotive industry. Three most important crash scenarios, Full Frontal Impact (FFI), Offset Frontal Impact (OFI), and Side Impact (SI) are used in this study. Although, the combination of crashworthiness responses and vibration characteristics limits the minimization of mass, the contrast between rigidity for vibration and softening for crash responses addresses important considerations for magnesium application in car body structure. In addition, design optimization of the car body structure under two different criteria (crash and vibration) and specific details related to the computational modeling, response approximations, and optimization are presented and discussed.

2. Problem overview and optimization setup

Both crashworthiness and vibration design criteria of a full-scale Finite Element (FE) model of the 1996 Dodge Neon are considered. A set of 22 steel parts is selected depending on their influence on such properties as internal energy absorption and stiffness. These selected parts are replaced by magnesium alloy AZ31 to demonstrate the effect of material replacement on car weight reduction. The number of parts selected was twenty-two but due to symmetry in the design, the design variables were reduced to fifteen. Moreover, a multidisciplinary design optimization problem is set up for mass minimization of magnesium replaced parts with crashworthiness responses in three crash scenarios (FFI, OFI, SI) and vibration analysis responses as design constraints. The wall thicknesses of the selected parts were defined as the design variables. Internal energy absorption of the parts, intrusion distance of toe-board and dashboard, and the peak acceleration value were selected as the responses in crashworthiness study as well as the first three fundamental frequencies attributes obtained from the vibration analyses.

To study the effect of magnesium on structural stiffness, the single objective (SO) optimum design addressed by Parrish et al. [8] was selected for comparison. Fig. 1 shows those 22 steel parts which were considered to be replaced by magnesium alloy subjected to design optimization constraints which are extracted from the crashworthiness and vibration responses of the steel baseline. The constraints allow obtaining a lighter design without compromising the crashworthiness or vibration behavior of the baseline car model with steel parts. To facilitate this process, the design space was expanded by changing the bounds of design variables for magnesium replaced parts. To limit the overall computation effort, only 22 parts were selected for replacement by magnesium; however, should more parts be selected as design variables, more mass could be saved. The parts with darker shade shown in Fig. 1 are symmetric parts of the design.

Table 1 shows the specification for the selected parts at the steel baseline and the SO optimization design of Parrish et al. [8], and Table 2 shows the associated responses for the two baselines that are used as the design constraints in this study.

Mass minimization for the modified body structure is achieved by the optimization problem shown below.

$$\begin{aligned} &\text{Min} \quad f(\boldsymbol{x}) \\ &\text{s.t.} \quad g_i(\boldsymbol{x}) = R_i(\boldsymbol{x}) - R_i^b \le 0; \quad i = 1,8 \\ &\qquad\; g_i(\boldsymbol{x}) = R_i^b - R_i(\boldsymbol{x}) \le 0; \quad i = 9,14 \\ &\qquad\; 0.5\,\text{mm} \le x_j \le 8\,\text{mm}; \quad j = 1,15 \end{aligned} \tag{1}$$

where $f(\boldsymbol{x})$ is the objective function defined as the total mass of the selected components; the $g_{1-8}(\boldsymbol{x})$ constraints represent the design constraints on the intrusion distances of toe-board, dash board for FFI and OFI, intrusion distance of door for SI and acceleration of B-Pillar in all three crash scenarios. These responses are required to be less than or equal to their baseline values. The $g_{9-14}(\boldsymbol{x})$ constraints impose limits on the internal