Thin-Walled Structures 94 (2015) 500–511

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Reliability design optimization of vehicle front-end structure for pedestrian lower extremity protection under multiple impact cases

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ARTICLE INFO

Article history:
Received 9 March 2015
Received in revised form
14 May 2015
Accepted 18 May 2015
Available online 8 June 2015

Keywords:
Reliability optimization
Vehicle front-end structure
Pedestrian protection
Multiple impact cases

ABSTRACT

Injuries to the lower extremities are one of the major issues in vehicle to pedestrian collisions. To evaluate pedestrian lower extremity protection, the Transport Research Laboratory Pedestrian Legform Impactor (TRL-PLI) test has been conducted according to the specifications in European Union (EU) regulation. At the same time, a Flexible Pedestrian Legform Impactor (Flex-PLI), which has flexible femur and tibia, is examined in European New Car Assessment Program (Euro-NCAP) rating system. To minimize injury risks of pedestrian lower extremity, this paper presents the design optimization of a typical vehicle front-end structure subjected to two different impact cases of TRL-PLI and Flex-PLI. Several approaches involving sampling techniques, surrogate model, multiobjective optimization algorithm and reliability analysis are introduced and applied. Four different basis functions of radial basis function (RBF) surrogate model are adopted for achieving more accurate solutions for structural optimization and reliability analysis. It shows that the accuracy of the basis function is different and the best one is selected for approximate the objective and constraint functions. In order to take into account the effect of design variables uncertainty, the reliability-based design optimization (RBDO) is conducted, and a Monte Carlo Simulation (MCS) is adopted to generate random distributions of the constraint functions for each design. The differences of the different Pareto fronts of the deterministic optimization and RBDO are compared and analyzed in this study. Finally, the reliability-based optimum design result is verified by using test validation. It is shown that the pedestrian lower extremity injury can be substantially improved for meeting product development requirements through the proposed approach.
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1. Introduction

According to World Health Organization (WHO) statistical data, 22% of deaths on the world roads are pedestrians, and this proportion is as high as two thirds in some countries [1]. Meanwhile, the frequency of lower extremity injuries is higher in vehicle to pedestrian collisions. For example, serious lower extremity injuries from bumper contact occurred in 43% of seriously injured pedestrian cases in US, 35% in German and 43% in Japan [2,3]. Considering the significant number of pedestrian lower extremity injuries that have been involved in road fatalities, studies on the protection of pedestrian are in progress in a number of vehicle companies to develop automobile technology [4].

To evaluate the performance of lower extremity protection, two different subsystem legform tests have been used in the extensive government regulations and standards. In the European Union (EU) regulation, the Transport Research Laboratory Pedestrian Legform Impactor (TRL-PLI) test has been conducted using a legform impactor developed by Transport Research Laboratory [5]. The TRL-PLI legform impactor has a steel femur and tibia body, which are connected by knee bars. The Flexible Pedestrian Legform Impactor (Flex-PLI) has been discussed regarding its introduction into European New Car Assessment Program (Euro-NCAP) [6].

In general, millions of people are injured in traffic-related crashes while walking, and pedestrian injuries relate to impact speed, vehicle front-end structure et al. [7]. Pedestrian safety system can provide supplemental protection to pedestrians who are the most vulnerable road users [8]. So, researches on protection of pedestrian lower extremity have become a very important part in both the academe and automotive industry. For instance, Shin et al. [9] performed bumper size optimization by using response surface approximate optimization (RSAO) and the result

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http://dx.doi.org/10.1016/j.tws.2015.05.014
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could meet requirements of TRL-PLI impact. Lee et al. [10] researched the front-end structure for Flex-PLI impact. However, the above investigations on design optimization in the existing literature mainly focus on the single legform impactor. Matsui [11] investigated the characteristics of safety assessment results of different vehicle types in impact tests using the TRL-PLI and the Flex-PLI. The results showed that for an impact against a relatively stiff structure, the tibia injury assessment was different between the TRL-PLI and the Flex-PLI owing to their different sensor types. So, the vehicle front-end structure is subjected to multiple legform impactor cases which should be verified for the required regulation and standard. However, the traditional approach is to tune the design manually for each test mode separately. This is a very laborious process as a single design is work well for one load case, but may not work for another. It is therefore hardly to find a design that is work properly for all test modes. So, in this study, the optimization design method will be extended to deal with these problems.

Optimization design using numerical techniques and surrogate models has been considered as a promising alternative to structure design of vehicles. Surrogate modeling techniques, such as polynomial response surface (PRS), Kriging (KRG) and radial basis function (RBF) [12,13], allow the construction of models for the purpose of design exploration such as variable screening, optimization and reliability. They have been exhaustively adopted in engineering applications to alleviate the high computational burden and explore design space for an optimum. For instance, Jin et al. [14] compared RSM, KRG, RBF, and multivariate adaptive regression splines (MARS) using fourteen different problems, with one representing a complex engineering application. It was found that RBF was the best for overall performance on accuracy, robustness, and efficiency et al. Sun et al. [15] used the RBF metamodel to approximate the energy absorption characteristics of honeycomb type cellular material under crashing status and obtained satisfactory optimal results. Fang et al. [16] discussed the development, application, and accuracy of RBF in multiobjective crashworthiness optimization of a full-scale vehicle model. It was showed that the multiquadric function could produce the most stable RBF for all objective functions. To account for uncertainties of predictions, a simple and preferable way is to attempt different correlation functions, from which the best one can be selected according to the relative fitting accuracy by errors analysis. Hence it is essential for conducting different correlation functions, and then assessing the appropriateness of the correlation functions for a particular problem. In this study, four typical basis functions of RBF including Thin-plate spline, Gaussian, Multiquadric and Inverse multiquadric are adopted to optimize the vehicle front-end structure for minimizing injury risks of pedestrian lower extremity under multiple impact cases. The most accurate basis function is used to approximate the objective and constraint functions and then is connected to a reliability method to estimate failure probability.

All optimization problems cannot neglect the uncertainty, which exists in material properties, geometries and manufacturing precision etc. In order to take into account various uncertainty, Reliability-based design optimization (RBDO) is introduced and aims at finding a reliable optimum solution by converting the deterministic constraints into probabilistic ones. Many researchers have focused on this field. For example, Shi et al. [17] presented a stochastic sensitivity-analysis method for computing the sensitivities of probabilistic response by using Monte Carlo Simulation (MCS) incorporated with a metamodel, which is selected by using Bayesian metric considering data uncertainty. The results showed that crashworthiness is improved, and at the same time reliability is improved. Gu et al. [18] presented a practical approach of the RBDO for vehicle occupant protection system (OPS) performance development. Sinha [19] developed a reliability-based multiobjective optimization design for vehicle structural crashworthiness and occupant safety under side impact. Huang et al. [20] by means of the Taguchi method, the sensitivities of five design parameters for the bumper system were analyzed to reduce the lower extremity injuries based on TRL-PLI impact. These studies show that reliability-based design can greatly improve the reliability of vehicle front structure.

Nevertheless, vehicle front-end structural optimization for minimizing injury risks of TRL-PLI and Flex-PLI impact considering the uncertainty has received limited attention in the literature. Thinking for its significant practical value, this paper presents a comprehensive study approach of how different nondeterministic optimization schemes are performed in the design of vehicle front-end structure under multiple impact cases. However, such a technique would become computationally expensive when considering uncertainty in multiobjective framework. To overcome the issue, the most accurate basis function of RBF model is implemented, combining with an Optimal Latin Hypercube Sampling (OLHS). Besides, all design variables are assumed to be normally distributed in this study. After validating the surrogate model, the multiobjective particle swarm optimization (MOPSO) algorithm is applied to seek optimal solutions and Monte Carlo simulation (MC) is applied to perform the reliability analysis. As a result, different Pareto optimums are generated for deterministic and nondeterministic designs, respectively. These different Pareto optimums are finally compared in a quantitative fashion to provide some insights into the use of these different optimization schemes.

2. Theory and methodology

2.1. Reliability-based multiobjective optimization

A number of engineering designs often belong to multiobjective optimization problem (MOP) in nature, as they often involve more than one criterion. To study the tradeoffs of these design objectives and explore available design options, the deterministic MOP can be formulated as:

$$\begin{cases} \min \;\; f(\mathrm{x}) = (f_1(\mathrm{x}), f_1(\mathrm{x}), \ldots\ldots, f_Q(\mathrm{x})) \\ s.\,t. \;\;\; g_j(\mathrm{x}) \le 0, \quad j = 1, 2, \ldots\ldots, M \\ \qquad\qquad \mathrm{x}^L \le \mathrm{x} \le \mathrm{x}^U \end{cases} \tag{1}$$

where $f(\mathrm{x})$ is a objective vector in the design space, $g_j(\mathrm{x})$ is the function representing the constraints, Q and M are the number of objectives and constraints, x^L and x^U are the lower and upper bounds of the vector of design variables x, respectively. Generally, the deterministic optimum designs without considering the uncertainty of design variables frequently push design constraints to the limit of boundaries.

The reliable design indicates an optimization subjecting to probabilistic bounds on the constraints as:

$$\begin{cases} \min \qquad \mu(f_q(\mathrm{x})) \quad q = 1, 2, \ldots\ldots, Q \\ s.\,t. \;\; P(g_j(\mathrm{x}) \le 0) \ge R_j, \quad j = 1, 2, \ldots\ldots, M \\ \qquad\qquad \mathrm{x}^L \le \mathrm{x} \le \mathrm{x}^U \end{cases} \tag{2}$$

where μ is the vector of objectives mean and R_j is the desired reliability for satisfying functional constraint $g_j(\mathrm{x})$ ($g_j(\mathrm{x}) > 0$ indicates failure). The reliable optimization design uses the probabilistic constraints to consider uncertainty of the design variables and parameters, which can stop pushing design constraints to the limit of boundaries. The MCS technique is adopted to obtain the values of probabilistic constraints in this study [21].

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