Advances in Engineering Software xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Research paper

Shape optimization of automotive body frame using an improved genetic algorithm optimizer

Qin Huan, Guo Yi, Liu Zijian*, Liu Yu, Zhong Haolong

State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, PR China

ARTICLE INFO

Keywords:
BIW frame
Shape optimization
Penalty-parameterless approach
Improved genetic algorithm
Meta-heuristic algorithms
Integrated optimizer

ABSTRACT

At conceptual design stage, the cross-sectional shape design of automotive body-in-white (BIW) frame is a critical and intractable technique. This paper presents shape optimization using an improved genetic algorithm (GA) optimizer to promote the development of auto-body. The shape optimization problem is formulated as a mass minimization problem with static stiffness, dynamic eigenfrequency and manufacture constraints. Then the transfer stiffness matrix method (TSMM) proposed in our previous study is adopted for the exact static and dynamic analyses of BIW frame. Additionally, the scale vector method is introduced to remarkably reduce design variables. Especially, an integrated object-oriented GA optimizer, which employs penalty-parameterless approach to handle constraints, is developed to solve constrained single-objective and multi-objective optimization problems. The optimizer is benchmarked on 12 test functions and compared with a variety of current meta-heuristic algorithms to demonstrate its validity and effectiveness. Lastly, the optimizer is applied to the solution of BIW shape optimization.

1. Introduction

Automotive body-in-white (BIW) frame is the significant load-carrying component of automotive body, and it consists of semi-rigid connected thin-walled beams (TWBs) that are manufactured from multiple stamped metal sheets, which are assembled by spot welding and bolting [1], as shown in Figs. 1 and 2. The complex shapes and thicknesses of TWBs determine the cross-sectional properties, e.g., areas, moments of inertia and torsional constants, which profoundly affect the performances of automotive body, such as static stiffness, NVH (Noise, vibration and harshness), and crashworthiness. Thus, determining the optimal cross-sectional shapes and thicknesses of TWBs is one of the most important issues at conceptual design stage. However, to date, there is no available commercial software for cross-sectional shape design. Consequently, design engineers mostly rely on empirical and intuitive trial-and-error approach, which is laborious, time-consuming and unreliable, to design cross-sectional shape. At conceptual design phase, initial cross-sectional shapes are extracted from the benchmarking auto-body, selected from the cross-section database, or drawn by engineers. Engineers endeavor to design optimal cross-sectional shapes and thicknesses aiming at obtaining a lightweight BIW frame without violating the required performance targets and fabrication constraints. That is, this is typically a shape optimization problem.

Vinot et al. [2] presented a shape optimization methodology for the design of thin-walled beam-like structures considering dynamic behavior. Apostol [3,4] proposed a general optimization method for arbitrary cross-section of a truss or beam. Nevertheless, studies in Refs. [2–4] paid little attention on handling manufacture and assembly constraints, which is one of the difficulties in BIW frame cross-sectional shape optimization. Yoshimura et al. [5] took two manufacture and assembly constraints into consideration. These constraints were introduced by Zuo [6–8]. The second difficulty arises from the large amount of design variables, especially for shape optimization problems of multiple cross-sections. Yim et al. [9] defined scale vectors as design variables rather than control point coordinates. The scale vector method notably reduced the amount of design variables, and enabled the cross-sectional optimization of multiple TWBs. The third difficulty is the solution of shape optimization. With fabrication constraints considered, BIW frame shape optimization is a constrained nonlinear optimization problem. On account of that these fabrication constraints cannot be explicitly expressed by formulas, thus gradient-based variables, e.g., the sensitivity of stamping constraint with respect to design variables cannot be calculated. Consequently, genetic algorithm (GA) is extensively used in the solution of this problem in conjunction with penalty method. However, how to set the penalty coefficients for penalty functions is a tough and inefficient technique. Deb et al. [10,11]

* Corresponding author.
E-mail address: zijianliu@hnu.edu.cn (Z. Liu).

https://doi.org/10.1016/j.advengsoft.2018.03.015
Received 15 November 2017; Received in revised form 16 March 2018; Accepted 25 March 2018

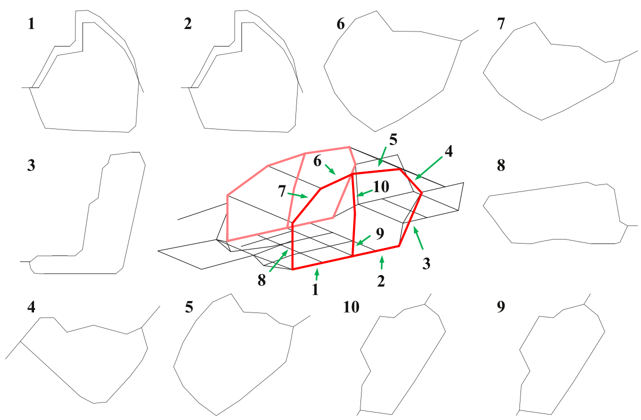

Fig. 1. BIW frame and its TWBs' cross-sections.

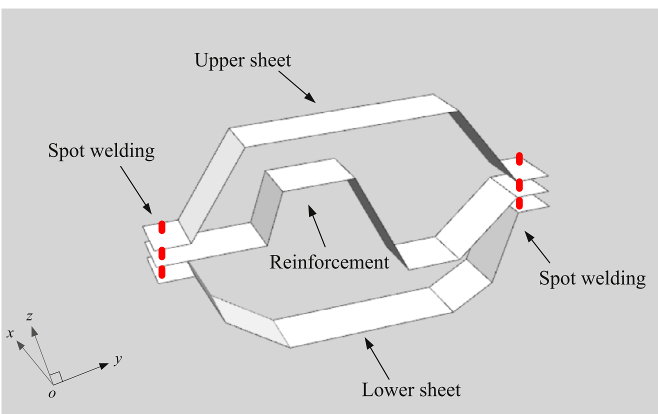

Fig. 2. Fabrication of a typical cross-section for TWBs.

implemented different penalty-parameterless constraint-handling approaches for single-objective and multi-objective optimization problems.

Moreover, studies in Refs. [2–9] are based on finite element method (FEM), which is an approximate method. This paper adopts the transfer stiffness matrix method (TSMM) proposed in our previous study [12], on account of that (a) firstly, at conceptual design stage, BIW frame can be simplified as a semi-rigid space frame structure, to which TSMM can be directly applied with less degrees of freedom; (b) furthermore, TSMM is an exact method both for static and dynamic analyses of framed structures, and it is more accurate than traditional FEM. Shape optimization of multiple cross-sections is implemented for lightweight design of BIW frame at conceptual design phase, with consideration of static bending stiffness, torsional stiffness, first-order free vibration eigenfrequency, and three manufacture constraints. Especially, an improved GA optimizer (IGA optimizer for short hereinafter), which employs penalty-parameterless approach to handle constraints, is developed to solve this constrained nonlinear optimization problem. The validity and effectiveness of the optimizer are demonstrated by benchmarking on multiple classical numerical examples, and then the optimizer is applied to BIW frame shape optimization.

The remainder of this paper is organized as follows. In Section 2, the formulation of cross-sectional properties and scale vector method are reviewed and summarized. In Section 3, the shape optimization of multiple cross-sections is formulated. In Section 4, the development of the IGA optimizer is introduced. In Section 5, benchmark results and discussion of IGA optimizer are given. Afterwards, the shape optimization is solved using IGA optimizer in Section 6. Finally, conclusions are made in Section 7.

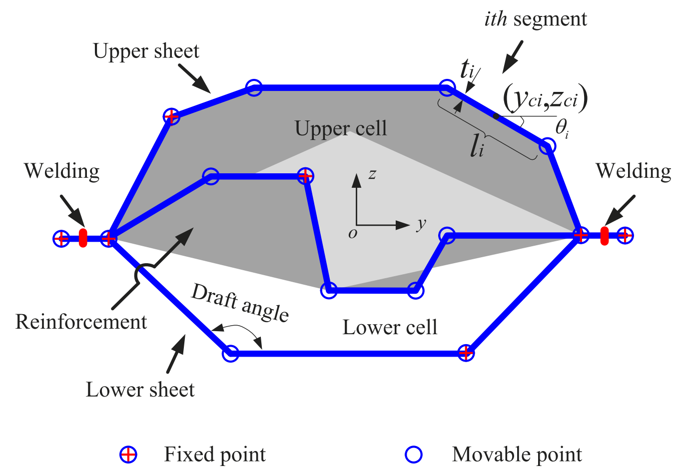

Fig. 3. A typical cross-sectional shape in BIW frame.

2. Formulation of cross-sectional properties and scale vector method

2.1. Formulation of cross-sectional properties

A typical cross-section example of the TWB, e.g., the rocker, is illustrated in Fig. 3. Three stamped metal sheet parts are spot-welded together to form the cross-section. Every sheet comprises several segments, each of which can be regarded as a rectangle with certain length and thickness. Thus the cross-sectional area is namely

$$A = \sum_{i=1}^{n} l_i t_i \tag{1}$$

where n is the total number of segments of a specified cross-section; l_i is the length of the ith segment, and t_i is thickness.

The cross-sectional centroid coordinate is given by

$$c_y = \frac{1}{A}\sum_{i=1}^{n} l_i t_i y_{ci} \text{ and } c_z = \frac{1}{A}\sum_{i=1}^{n} l_i t_i z_{ci} \tag{2}$$

in which (y_{ci}, z_{ci}) is the coordinate of the ith segment centroid.

The inertia moments I_y and I_z, and second area moment I_{yz} with regard to the centroid are calculated by

$$I_y = \sum_{i=1}^{n}\left(\frac{l_i t_i^3}{12}\cos^2\theta_i + \frac{l_i^3 t_i}{12}\sin^2\theta_i + l_i t_i y_{ci}^2\right) \tag{3}$$

$$I_z = \sum_{i=1}^{n}\left(\frac{l_i t_i^3}{12}\sin^2\theta_i + \frac{l_i^3 t_i}{12}\cos^2\theta_i + l_i t_i z_{ci}^2\right) \tag{4}$$

$$I_{yz} = \sum_{i=1}^{n}\left(\frac{l_i^3 t_i - l_i t_i^3}{24}\sin 2\theta_i + l_i t_i y_{ci} z_{ci}\right) \tag{5}$$

in which θ_i is the angle between the ith segment and the positive y axis. From I_y, I_z and I_{yz}, the principal inertia moments are derived as

$$I_{\max} = \frac{1}{2}(I_y + I_z) + \sqrt{\frac{1}{2}(I_y - I_z)^2 + I_{yz}^2} \tag{6}$$

$$I_{\min} = \frac{1}{2}(I_y + I_z) - \sqrt{\frac{1}{2}(I_y - I_z)^2 + I_{yz}^2} \tag{7}$$

The counterclockwise angle φ of principle inertia direction about the reference y axes is expressed as

$$\varphi = \frac{1}{2}\tan^{-1}\left(\frac{-2I_{yz}}{I_z - I_y}\right) \tag{8}$$

The general formula for the torsional constant is written as