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Research paper

An object-oriented MATLAB toolbox for automotive body conceptual design using distributed parallel optimization

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ABSTRACT

Appropriate structural analysis and optimization methods are of great significance for the conceptual design of automotive body-in-white (BIW) structure. This paper simplifies BIW structure as a spatial semi-rigid framed structure to provide early-stage predictions. Then a novel exact transfer stiffness matrix method (TSMM) is proposed for both static and dynamic analyses of three-dimensional semi-rigid framed structures. The matrix storage and equation solution techniques for large-scale engineering structures are also considered. Additionally, a size optimization mathematical model for BIW conceptual structure is formulated and solved by genetic algorithm (GA). Afterwards, to promote the conceptual design of BIW structure, an object-oriented MATLAB toolbox, based on TSMM, is developed. The Unified Modeling Language (UML) and strategy design pattern are employed to facilitate the development of the toolbox. Distributed parallel computing technique is adopted to speed up the former sequential optimization algorithm with simple modifications. Lastly, the validity of this easy-used toolbox is demonstrated by a benchmarking auto-body.

1. Introduction

Conceptual design is vital in automotive body development and it has a great effect on later design work. Lightweight design is a main topic for automotive body-in-white (BIW) conceptual design, and appropriate structural analysis and optimization methods are of great significance. Finite element method (FEM) has been extensively used in the structural analysis and optimization of auto-body. There are two distinct classes of finite element (FE) models, i.e., the detailed and conceptual. The detailed FE model is meshed by shell elements, which achieve computational accuracy by precisely simulating component geometries. However, at the conceptual design phase, there may be no sufficient information to construct a detailed computer-aided-engineering (CAE) model. Thus a conceptual model is necessary to predict the required performance targets at the early stage, such as static stiffness, NVH (Nosie, vibration and harshness), and crashworthiness. Generally, BIW structure can be simplified as a spatial framed structure, consisting of joints and beams, as shown in Fig. 1. Then the BIW conceptual model is evaluated to provide early-stage predictions.

At the conceptual design phase, the crucial work is to construct an appropriate computational model, calculate and optimize BIW performance targets accurately and fast. Donders et al. proposed a “reduced beam and joint modelling” approach [1,2], in which the detailed FE model was replaced by simplified beam elements, whose cross-sectional properties can be calculated from the predecessor FE model. Not only the beam cross-sectional properties, but also joint flexibility is significant. If beam elements are treated with rigid connections without considering the flexibility of joints, the global bending stiffness of simplified BIW structure is approximately twice the actual bending stiffness of real vehicle [3]. In Ref. [4], both “super-element elastic joint” and “tri-spring joint” were studied, and the latter was thought to have several advantages. Repeated meshing of the detailed auto-body model in commercial finite-element-analysis (FEA) software is laborious and time-consuming. Furthermore, the designer is required to have rich experience, so several specialized software tools have been developed. Toyota Central R&D Labs [5] proposed a first order analysis concept for BIW designers, and developed a piece of FEA software, whose expansibility and maintainability are poor for the Microsoft/Excel base. In Refs. [6–8], Zuo WJ et al. developed the object-oriented “Vehicle Body – FDO” software based on .NET framework. The BIW structure was constructed by semi-rigid beam hybrid elements, and the mathematical model was built based on FEM.

However, FEM is an approximate method. A normal beam element should be divided into many segments to achieve higher accuracy, especially for dynamic analysis. In this paper, the BIW

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0965-9978/

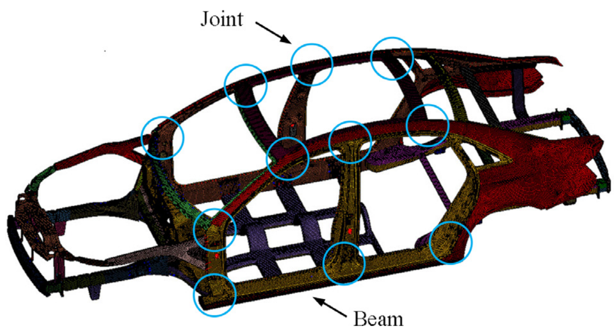

Fig. 1. The BIW conceptual model.

conceptual model is established by the semi-rigid beam element; and an exact transfer stiffness matrix method (TSMM) is proposed for both static and dynamic analyses of three-dimensional semi-rigid framed structures. In this method, for the rigid beam element, the force-displacement relationships are based on the exact solutions of the underlying differential equations. Consequently, the shape functions and stiffness matrices are exact. For the semi-rigid beam, the transfer matrix method (TMM) [9] is used to condense the semi-rigid beam element as a super element. Also, the stiffness matrix storage and equation solution techniques for large-scale engineering problems are considered. In addition, a preliminary cross-sectional size optimization problem for BIW lightweight design is formulated and solved by genetic algorithm (GA). To promote the conceptual design of BIW structure, an object-oriented MATLAB toolbox (named "Automotive Body Conceptual Design" toolbox and "ABCD" toolbox for short) with user-friendly graphical user interface (GUI) is developed. Distributed parallel computing is adopted to evidently speed up the former sequential algorithm of size optimization with simple modifications. At last, the validity of this easy-used toolbox is demonstrated by a benchmarking auto-body.

The rest of this paper is organized as follows. In Section 2, the derivation of TSMM is introduced. In Section 3, the formulation and solution of the mathematical model of preliminary cross-section size optimization are addressed. The framework of this MATLAB toolbox and distributed parallel computing are depicted in Section 4. Afterwards, in Section 5, numerical examples are given to demonstrate the effectiveness of this toolbox. Finally, conclusions are made in Section 6.

2. BIW structural analysis using TSMM

In TSMM, a structure is modeled as an assemblage of members connected at their ends to joints. A member is defined as a prismatic part of the structure. A joint is defined as a structural part of infinitesimal size to which the ends of the members are connected. And the geometrical model of a structure is represented by a line diagram, on which each member is depicted by a line coinciding with its centroidal axis.

The geometrical model of the BIW conceptual structure is shown in Fig. 2. The ith member is identified by '*Mi*', and the jth joint is identified by '*Jj*'. A semi-rigid beam consisting of a rigid beam and two semi-rigid connections, each of which is composed of three rotational springs around local x, y, and z axes, is constructed to simulate the actual auto-body joint flexibility. The springs are all zero-length and massless, as shown in Fig. 3, where k_{ij} ($i = b,e;\ j = 4,5,6$) are the stiffness coefficients of rotational springs around x, y, and z axes, respectively; the symbols 'b' and 'e' denote the beginning joint and end joint, respectively. Timoshenko beam theory is introduced to consider the transverse shear deformations and rotary inertia effect of the beam element.

2.1. The TSMM formulation

2.1.1. The derivation for rigid beam stiffness matrices

With the use of static equilibrium equations and D'Alembert's principle (i.e., dynamic equilibrium equations), the exact governing equations of motion of the rigid beam undergoing static equilibrium or free vibration can be symbolically represented in general as

$$L(\bar{\mathbf{u}}) = \mathbf{0} \tag{1}$$

where L is a differential operator; $\bar{\mathbf{u}}$ is the corresponding displacement vector, and

$$\bar{\mathbf{u}} = \begin{cases} \bar{\mathbf{u}}(x), & \text{static equilibrium} \\ \bar{\mathbf{u}}(x,t), & \text{free vibration} \end{cases} \tag{2}$$

where x is a spatial coordinate, and t is the time. Then the displacement vector $\bar{\mathbf{U}}$ can be represented by the member end

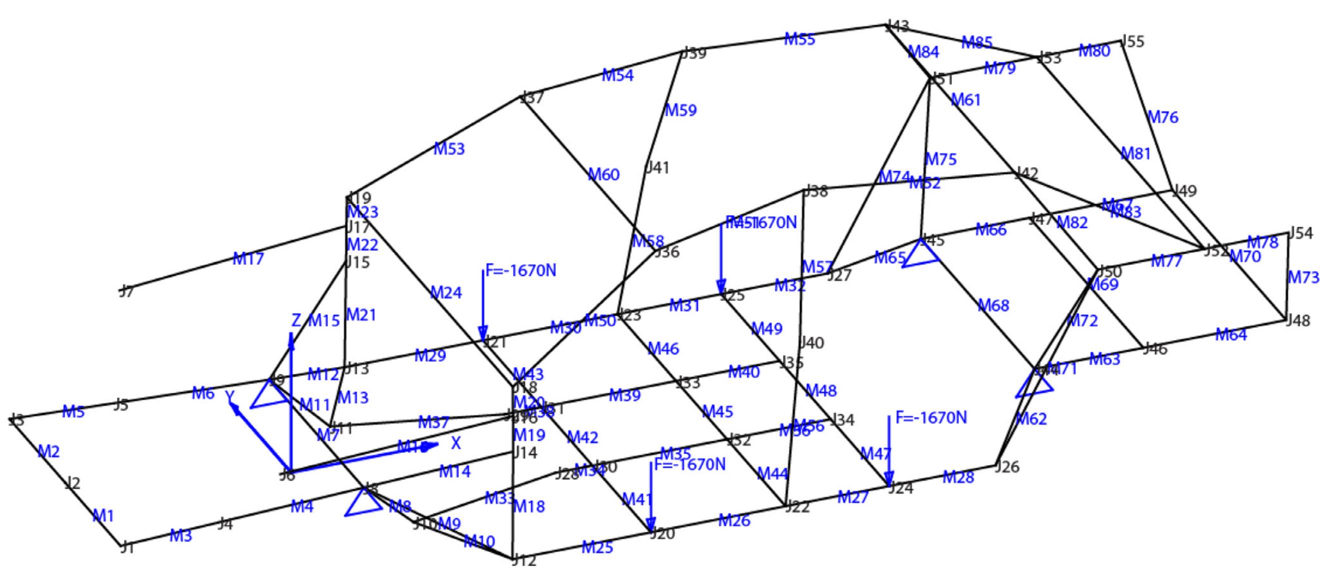

Fig. 2. The geometrical model of BIW conceptual structure.