Computer-Aided Design 57 (2014) 29–40

Contents lists available at ScienceDirect

Computer-Aided Design

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

Compliant assembly variation analysis of aeronautical panels using unified substructures with consideration of identical parts

Jia Lin [a], Sun Jin [a,*], Cheng Zheng [b], Zhimin Li [a], Yinhua Liu [c]

[a] *State Key Laboratory of Mechanical System and Vibration, Shanghai Key Lab of Digital Manufacture for Thin-Walled Structures, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China*

[b] *Shanghai Aircraft Manufacturing Co., Ltd., Shanghai 200436, PR China*

[c] *School of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai 200093, PR China*

HIGHLIGHTS

- Finite element models of compliant parts are condensed into unified substructures.
- Substructures are reused among identical parts by transformation.
- The propagation of deviations during assembly is modeled based on substructures.
- An aeronautical panel assembly case is studied following the proposed method.

ARTICLE INFO

Article history:
Received 17 February 2014
Accepted 7 July 2014

Keywords:
Compliant variation analysis
Assembly
Aeronautical panel
Substructure

ABSTRACT

The assembly process of aeronautical panel usually involves numerous parts and subprocesses. Thus a large number of Finite Element Analysis (FEA) runs are required to construct its compliant Deviation Propagation Model (DPM), when using the traditional compliant assembly variation analysis methods such as the Method of Influence Coefficients and the Linear Contact method. In this paper, an efficient DPM construction method based on substructures is proposed to reduce the modeling complexity. Finite element models of compliant parts are condensed into substructures which have relatively fewer Degrees of Freedom (DOFs). And for the identical parts commonly used in the aeronautical panels, once the substructure of one part is generated, the substructures of the others can be obtained by transformation of the generated one. By properly selecting the retained DOFs, the same substructures are applicative throughout the overall modeling process. Based on these unified substructures, the DPM of aeronautical panel assembly process is constructed, without executing extra FEA runs. A case study on a panel subassembly of the side fuselage is used to illustrate the proposed method. The results show that, this method reduces the model size as well as the model construction work, while maintaining the same accuracy as complete finite element analysis conducted in a commercial software package.

1. Introduction

The skin–frame structured panels, as shown in Fig. 1(a), are widely used in the aerospace industry, especially in the fuselage manufacturing [1]. As important components of an aircraft, the geometrical quality of the panel subassemblies casts significant influence on the feasibility of subsequent assembly processes, as well as the aerodynamic characteristics and fatigue durability of the aircraft. Assembly variation analysis is an effective theoretical tool to control geometrical quality, i.e., the geometrical variations. Especially in the product development stage, this tool is widely adopted to predict the variation propagation in the assembly process and help to optimize the design [2–5].

The kinematics-based methods were earlier developed to model variation propagation in the assembly process [6–9]. However, for compliant parts, geometrical deviations are not only generated by kinematic motions but also by deformations introduced by loads or overconstraints. Parts of aeronautical panels are usually compliant since they are characterized by large size and small thickness, and subject to overconstraints when being assembled, as shown in Fig. 1(b); hence deformations should be taken into consideration in the assembly variation analysis of aeronautical panels.

* Corresponding author. Tel.: +86 21 34206306.
E-mail address: jinsun@sjtu.edu.cn (S. Jin).

http://dx.doi.org/10.1016/j.cad.2014.07.003

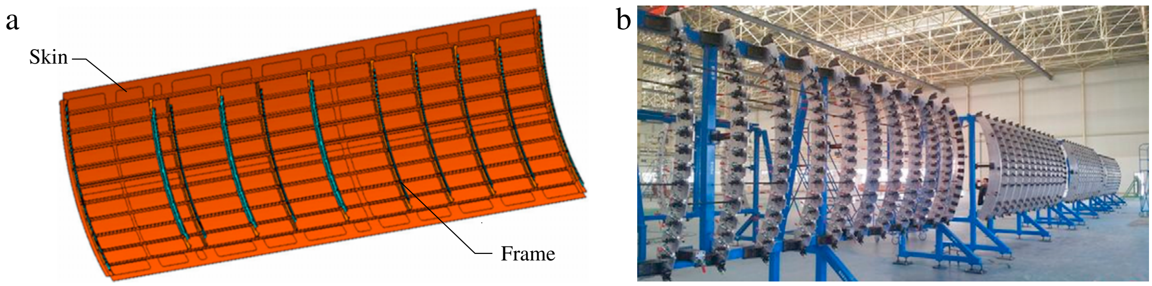

Fig. 1. An aeronautical panel subassembly of mid fuselage and its assembly fixture.

To account for deformations of compliant parts, theories of elastic mechanics were introduced into variation analysis [10]. Due to the irregular shapes and complicated boundary conditions of realistic parts, it is usually impossible to solve the assembly mechanics problems analytically, yet Finite Element Method (FEM) is needed to model the parts and resolve for numerical solutions. The most straightforward way to perform compliant variation analysis using FEM is the Direct Monte Carlo method [11–13]: Finite Element Analysis (FEA) is executed to analyze the assembly deformation for a deterministic case, while Monte Carlo simulation is adopted to repeat the analysis iteratively to obtained enough statistical samples. The Direct Monte Carlo method is simple and robust, and can produce more accurate results integrating complicated nonlinear FEM [12,13]; however it is very time-consuming since FEA needs to be run iteratively.

To improve the efficiency of compliant variation analysis, Liu and Hu [11] developed the Method of Influence Coefficient (MIC). Based on linear elastic assumption, sensitivity matrices were used to formulate the relationship between the part deviations and the assembly spring-back deviations. These sensitivity matrices can be obtained using the unit force response method, which is substantially a regression method using the FEA results as sample data. Since only a few variables, e.g., the displacements at weld locations are considered, a sensitivity matrix based model is usually much smaller than the complete FEM models; hence the efficiency is improved significantly compared to the Direct Monte Carlo method.

Researchers from Brigham Young University developed another method, i.e., the Linear Contact Method to account for the gap-closure deformation in variation analysis [14–16]. The equivalent deformation of parts being fastened was formulated through an Equivalent Stiffness, which was composed with the reduced stiffness matrices of parts at the fastening nodes. These reduced stiffness matrices were obtained using substructuring method. It is a more flexible method than the unit force response method, since specific displacement boundary conditions needed not to be pre-introduced.

The MIC and the Linear Contact Method have significantly improved the efficiency of compliant variation analysis, and made it more efficiency-acceptable to further perform or integrate advanced analysis, such as multistage assembly analysis, process optimization and contact analysis. Integrated with state space modeling method [17,18], the MIC were extended to multi-station assembly systems by Camelio et al. [19] and Yue et al. [20]. In combination of MIC and nonlinear programming, Camelio et al. [21] and Cai [22] conducted robust fixture design. Based on MIC, Long [23] and Jin et al. [24] conducted sensor placement optimization of sheet metal assembly, Wärmefjord et al. [25] optimized the spot welding sequence. Based on MIC as well, Dahlström et al. [26], Gerbino et al. [27] and Ungemach et al. [28] developed different strategies to consider the contact effect in compliant variation analysis.

Though a much leaner Deviation Propagation Model (DPM) can be obtained using MIC or linear contact method, the process of modeling may be complicated since FEA runs must be executed to acquire the sensitivity matrices or reduced stiffness matrices for every substep of the assembly process. This is especially the case when the assembly process involves a large number of parts and subprocesses, such as the assembly of aeronautical panels. To improve the efficiency of DPM construction, a substructure based method is proposed in this paper to perform compliant assembly variation analysis. Following this method, Finite Element (FE) models of compliant parts are condensed into substructures, while identical parts are considered that once one of their substructures is generated, the others can be obtained just by transformation of the generated one. By properly selecting the retained Degrees of Freedom (DOFs), the same substructures are applicative throughout the overall modeling process. Based on these unified substructures, the DPM of aeronautical panel assembly process is constructed, without needing to carry out extra FEA runs. And with Monte Carlo (MC) simulation on the attained DPM, statistical variation analysis is performed eventually.

This paper is organized as follows: Section 2 presents the model reduction method of substructuring, and the transformations of substructures. Then in Section 3, the process of DPM construction based on substructures is illustrated. Section 4 concludes the process of performing statistical variation simulation combining the DPM and MC method. A case study is presented in Section 5. And finally, conclusions are drawn in Section 6.

2. Substructuring of compliant parts

The FE models of realistic parts usually consist of great amount of discrete nodes and thus have large DOFs, which will bring expensive computational cost in the variation analysis. In this section, the substructuring method is used to condense a complete FE model into a leaner substructure and hence reduces the model size.

2.1. Static condensation of FE models into unified substructures

For a part made of linear elastic material which deforms within its elastic limit, the linear relationship between its displacements and the forces can be formulated as

$$\begin{bmatrix} \tilde{\mathbf{K}}_{\mathrm{cFcF}} & \tilde{\mathbf{K}}_{\mathrm{cFcu}} & \tilde{\mathbf{K}}_{\mathrm{cFr}} \\ \tilde{\mathbf{K}}_{\mathrm{cucF}} & \tilde{\mathbf{K}}_{\mathrm{cucu}} & \tilde{\mathbf{K}}_{\mathrm{cur}} \\ \tilde{\mathbf{K}}_{\mathrm{rcF}} & \tilde{\mathbf{K}}_{\mathrm{rcu}} & \tilde{\mathbf{K}}_{\mathrm{rr}} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_{\mathrm{cF}} \\ \mathbf{u}_{\mathrm{cu}} \\ \mathbf{u}_{\mathrm{r}} \end{Bmatrix} = \begin{Bmatrix} \mathbf{F}_{\mathrm{cF}} \\ \mathbf{F}_{\mathrm{cu}} \\ \mathbf{F}_{\mathrm{r}} \end{Bmatrix}. \quad (1)$$

According to the characteristics on boundary conditions during the assembly process, DOFs are generally fall into three categories: (1) DOFs subject to constant loads during the assembly process, e.g., free DOFs subject to zero loads or constant environmental loads such as gravity, decorated with a subscript “cF”; (2) DOFs whose displacements remain constant during the assembly process, decorated with a subscript “cu”; (3) DOFs of which both displacements and loads are variables during the assembly process. They will be retained for the variation analysis, decorated with a