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Computer Aided Tolerancing of Composite Elevator Assembly Involving Clamping Forces Coordination

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Abstract

Clamping forces are applied to the composite elevator due to the stochastic deviations, and in turn affect the stackup of deviations. The paper presents a computer aided tolerancing of composite elevator assembly involving clamping forces coordination. Based on the verified FEA model, the clamping force modified probability distribution is obtained. The tolerance simulation is conducted with the modified distribution. Principal component analysis is employed to extract the main deformation mode of the composite elevator from the tolerance simulation results. The clamping forces are coordinated based on the extracted deformation mode to accomplish the specifications of the joints.

Keywords: Tolerance Simulation; Clamping Force; Principal Component Analysis

1. Introduction

CAT (Computer Aided Tolerancing) work focuses on the stackup of deviations from different parts of the mechanisms and structures. The designer defines the set of tolerance chains and the tolerance values in the CAT software. Based on the designed positioning scheme and parts deviations, the CAT software will provide the results of tolerance chains calculated with the worst case or statistical approach. A good tolerancing analysis can predict or validate a manufacturing and assembly process from design. For a given assembling process, clamping forces contribute to the stackup of deviations and should be considered during the course of CAT procedure.

Composite elevator is one important assembly in the aircraft (Fig.1). It is composed with the metallic and composite components: the nose ribs, the forward spar, the metallic joints, ribs and the skin panels etc. The elevator connects with the horizontal stabilizer by several hinge joints, and these joints are subject to a set of coaxial tolerance requirements which determine the trajectory of the elevator. The hinge joints are in different positions along the forward spar.

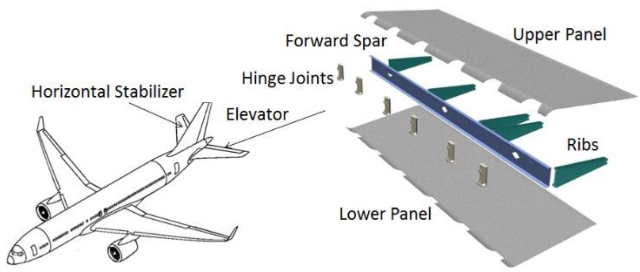

Fig.1. Structure of the composite elevator.

The forward spar, a kind of Carbon Fiber Reinforced Plastic/Polymer (CFRP) C-beam, forms the front structures of the elevator. When the forward spar comes out of the mould, there are spring-in deviations in it. Due to its dimension in length direction, the forward spar is clamped with a certain number of clamping forces in order to hold it in position when assembling. Because of the anisotropy of the composites, different clamping forces are applied to the forward spar according to its variable thicknesses and cross-sections along the length in order to adjust the position and orientation of the

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hinge joints. These clamping forces are coordinated with each other in order to satisfy not only the position and orientation tolerances, but also the whole coaxial tolerance.

The paper presents a computer aided tolerancing of composite elevator assembly involving clamping forces coordination, especially focusing on the spring-in deviations in the CFRP forward spar. Based on the verified finite element model, the clamping force modified probability distribution of the CFRP forward spar is obtained. The composite elevator tolerance simulation is conducted with a CAT software to analyze the stackup of deviations with the modified probability density function. Principal component analysis (PCA) is employed to extract the principal deformation mode of the CFRP forward spar from the simulation results. Then the clamping forces are coordinated according to the principal deformation model to accomplish the functional tolerance [1] of the hinge joints.

2. Literature Review

CAT work focuses on the stackup of deviations from different parts of the mechanisms and structures. For a given assembly process, the dimensional variations for flexible components come mainly from three sources, i.e. the part variation, the tooling variation, and the process variation. Many researches are conducted for assembly precision control, variation prediction of the Aerospatiale product assembly.

Saadat [2] studied the wing-box assembling at Airbus UK to quantify the deformation of assembling the wing panels onto the structure. Wang [3-7] studied the process control in the horizontal stabilizer assembly. FEA modeling, multilevel analysis and principal component analysis methods were employed to identify sources of variation, especially edges and ribs, in the assembling process. A Swedish research group conducted research on variation simulation and design for assembly [8-10]. They developed a simulation and visualization tool and it utilizes a computer-aided tolerancing package (RD&T) for assembly variation simulation.

Due to the brittle nature of composite, the composite part may experience fiber buckling, fiber breakage, matrix cracking, delamination, or by a combination of these failures if the prescribed clamping forces are too great. Inadequate clamping forces determination can lead to conservatively-designed assembling processes, which amount to precision and efficiency penalties in aircraft structures assembling. Raghu [11] analytically modeled the effect of clamping sequence on part positioning error, and an algorithmic procedure designed to understand how forces and deformations change as clamps are applied sequentially was presented. Polini [12] reported a method for tolerance analysis of a composite flaperon assembly involving free-form surfaces based on dimensional and geometrical tolerance. The influence of the tolerances applied to the ten components of the flaperon on the value of the gap at the interfaces among each couple of components has been deeply investigated by means of the proposed method. To reduce the deformation of the workpiece–fixture system and improve the performance of the fixture, Liu [13] proposed an optimization method for fixture layout and clamping force plan. Wang [14-16] proposed a finite element model of the composite beam to determine the maximal forces during the course of clamping.

Many challenges still exist to understanding structural behavior in composite aircraft structures assembling. The unavoidable fabrication deviations [17-19] comes from the spring-in, the thickness variations, and the form deviation etc. Wang [20] studied the effect of spring-in distortion in composite C beam on strength of the composite-metallic material beam. Corrado [21] presented a method for the tolerance analysis of a tail beam assembly involving free-form surfaces with large dimensions. The influence of the tolerances on the other requirements of the tail beam connected with the motion drive was studied. Peng [22] presented an integrating the unified Jacobian-Torsor model and Monte Carlo simulation techniques for the 3D statistical tolerance analysis of the piston aero engine assembly.

3. Composite Elevator Assembly

The composite elevator consists of metallic joints and the composite components (Figure 1): the forward spar, the ribs, and the skin panels etc. The spar forms the front structures of the elevator, and it is adhesive-bonded together with the skin panels and the ribs to form the elevator structure. The assembly relation of the composite elevator is represented with the Datum Flow Chain (DFC) [23], and the main assembling fixture is shown in Fig.2.

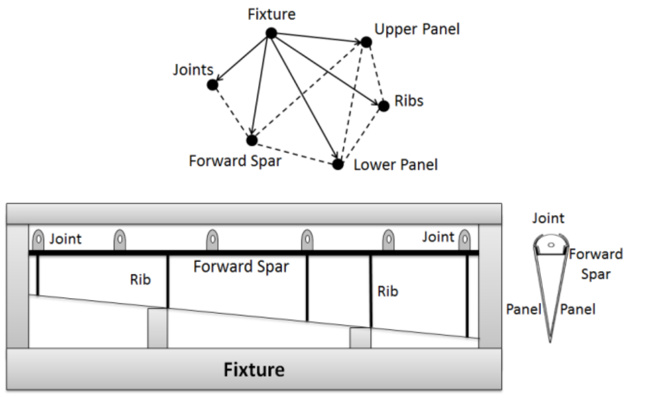

Fig.2. DFC of the composite elevator assembly and its assembling fixture.

Tolerances applied to the panels and the functional tolerance of the hinge joints are shown in Fig.3 and Fig.4.

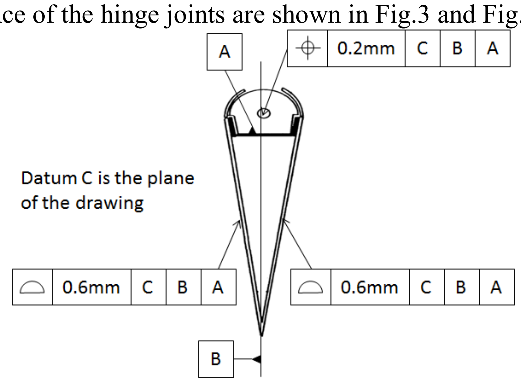

Fig.3. Tolerances applied to the panels.

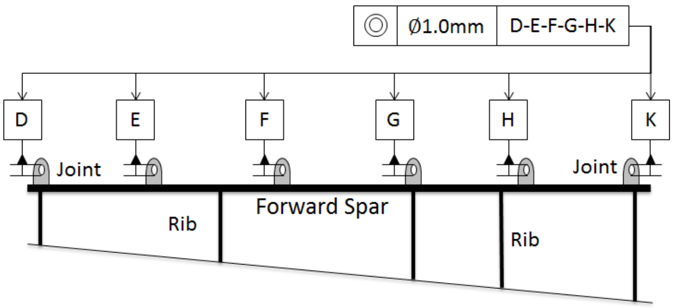

Fig.4. Functional tolerance of the hinge joints.

Based on the DFC, the tolerance simulation could be conducted for assembling the composite elevator with the CAT software, VSA [24]. Fig.5 is the tolerance simulation process of the composite elevator assembling.

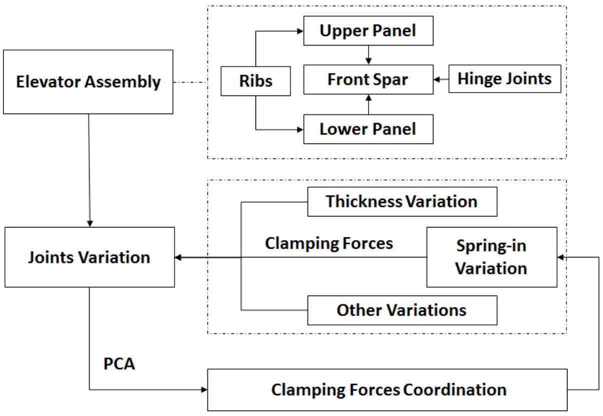

Fig.5. Tolerance simulation of the composite elevator.

4. Tolerancing Simulation of Elevator

Besides thickness variation and other variations, the spring-in variation is the main concern in the composite elevator tolerance simulation. Owing to high processing temperatures, the residual stresses in thermoplastic composites are inevitable. These residual stresses lead to a reduction in the enclosed angle in channel or angle components. This reduction in enclosed angle is referred to as the spring-in. The spring-in causes considerable difficulty for composites assembling, and brings un-expected assembling variation. The spring-in variations of the reported spar [16] are employed as the variation of the forward spar in the composite elevator (Fig.6). The spring-in variation was a normal distribution, and statistical indices (such as the average, the standard deviation, the maximum and the minimum etc.) were obtained.

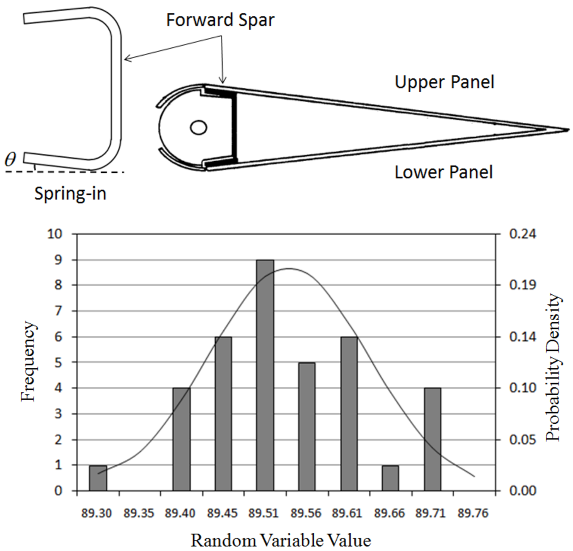

Fig.6. The spring-in variation and its distribution.

Six clamping forces are applied to the forward spar in order to accomplish the assembling. The positioning schemes and six clamping forces are defined for all parts of the composite elevator (Fig.7).

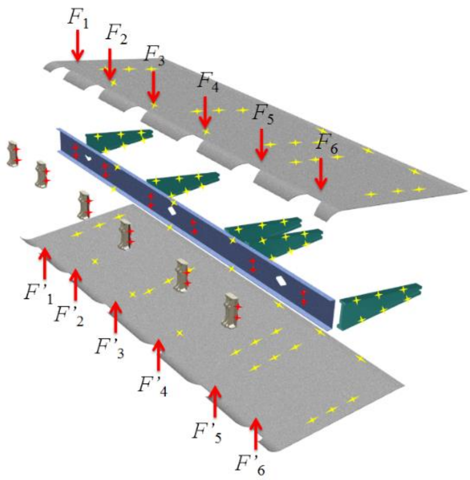

Fig.7. Positioning scheme and clamping forces in the composite elevator.

The clamping force applied to the forward spar affects the distribution of the forward spar. The clamping force modified distribution of the forward spar is shown in Fig.8 [16].

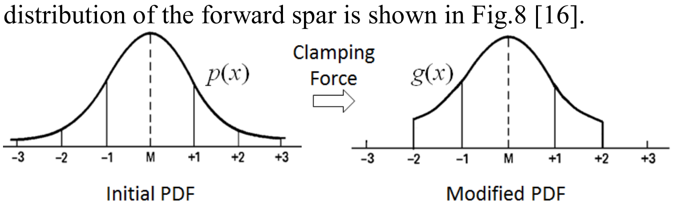

Fig.8. Clamping force modified PDF of the forward spar.

The clamping force modified PDF could be represented with the Pearson distribution in VSA (Fig.9).

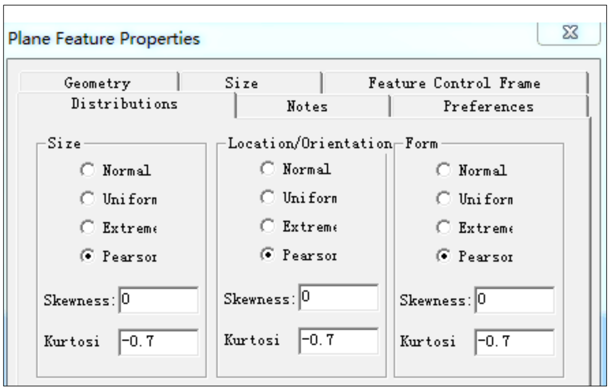

Fig.9. Pearson distribution in VSA.

Different clamping forces introduce different modifications in the forward spar's spring-in variations. For the tolerance simulation, all parts are put together virtually and 1000 iterations are conducted in VSA. The final assembling variations of the composite elevator are shown in Fig.10, and the detailed information is in Table 1.

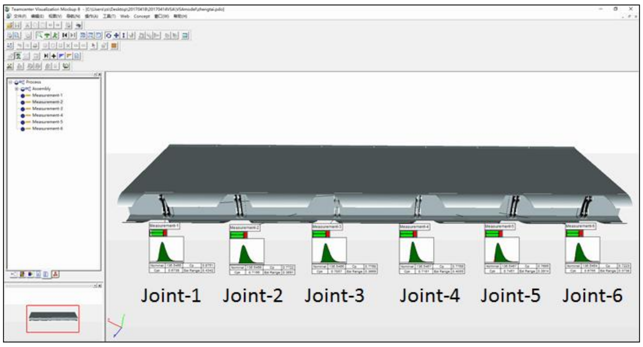

Fig.10. Tolerance simulation of the composite elevator.

Table 1. Six joints' variations of the composite elevator.

Joints	1	2	3	4	5	6
Means	136.62	135.72	134.12	135.57	137.86	136.61
Std.	0.0688	0.0656	0.0616	0.0692	0.0644	0.0632
Cp	0.6799	0.7224	0.7538	0.7128	0.7231	0.7676
%<Low Limit	1.9408	1.4300	1.6343	1.6343	1.4300	2.1450
%>High Limit	1.5322	1.8386	1.4300	1.7365	1.5322	1.2257
% Out of Spec.	3.4729	3.2686	3.0644	3.3708	2.9622	3.3708

5. PCA Based Clamping Forces Coordination

Different clamping forces result in different variation in the joints after assembling. The axial of the 6 joints center holes along the length should satisfy the specifications because the axial of the 6 joints affects the kinematic trajectory of the elevator and the forces in the joints. Clamping forces should be coordinated in order to accomplish the specification requirements.

PCA (Principal Component Analysis) is an effective tool for extracting the principal mode from potentially high-dimensional data sets. It maps the input space into a feature space via nonlinear mapping and then computes the principal components in that feature space. PCA is adopted to extract the principal deformation modes of the 6 joint points' variations in axial direction along the length. Eigenvalues and eigenvectors of the variations in Table 1 are shown in Table 2. Based on these features, clamping forces coordination can then be performed to accomplish the elevator assembling with the horizontal stabilizer.

Table 2. PCA results of the 6 joints' variations.

Comp-onent	Eigen-values	Contribution (%)	Joints					
			1	2	3	4	5	6
1	4.89	81.43	-0.41	0.30	-0.44	0.42	-0.44	-0.43
2	0.66	10.93	0.21	0.91	0.18	0.13	0.15	0.21
3	0.21	3.57	0.76	-0.21	-0.11	0.58	-0.14	-0.05
4	0.17	2.77	0.45	0.18	-0.28	-0.65	-0.15	-0.49
5	0.06	0.92	-0.06	-0.02	0.40	0.20	0.53	-0.72
6	0.02	0.39	-0.02	0.00	-0.72	0.06	0.68	0.12

The eigenvectors in Table 2 are sorted as their contributions. The first eigenvector, whose contribution is bigger than 80%, is the principal deformation mode of the axial holes along the length of the composite elevator (Fig.11).

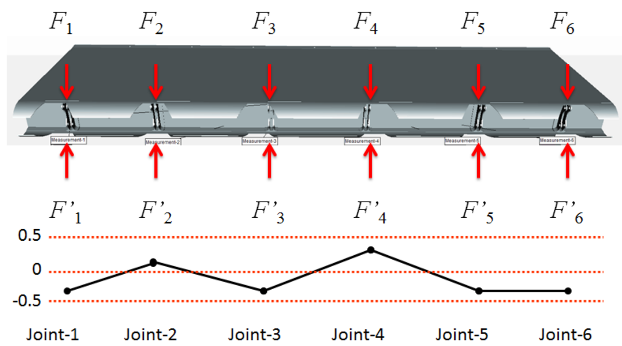

Fig.11. Axial holes' position along the length of the first principal component.

Clamping forces coordination strategy, add or decrease the clamping forces, could be obtained according to the principal deformation mode of the forward spar along the length (Fig.12).

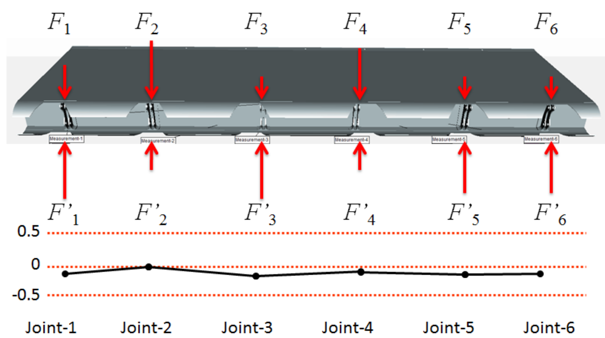

Fig.12. Axial holes' position along the length under coordinated clamping forces.

6. Conclusion

Clamping forces are applied to the composite elevator due to the stochastic deviations, and in turn affect the stackup of deviations. The paper presented a computer aided tolerance simulation of the composite elevator assembly involving clamping forces coordination, especially focusing on the spring-in deviations in the composite forward spar. The principal deformation mode of the composite elevator was extracted from the tolerance simulation results using the principal component analysis (PCA) method. The clamping forces are coordinated based on the extracted principal deformation model in axial direction along the length to accomplish the assembling. The PCA based clamping forces coordination method reported in the paper was effective in the composite elevator assembling tolerance stackup. It will enhance the understanding of the composite parts assembling, and help systematically improving the assembling efficiency in civil aircraft industry.

Remarks and Acknowledgements

In this article, we show several graphics in order to explain our method, but we do not need any of them for making practical computation. This project is supported by National Natural Science Foundation of China (Grant No.51775350).

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