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Abstract: In aeronautics the component compliance makes assemblies widely over-constrained, and the assembly process consists in adjusting linkage devices in order to satisfy functional requirements. The paper deals with a simulation method of the assembly process integrating the flexibility of the components which leads to the optimal values of the adjustment parameters so that functional requirements are ensured. The simulation is based on the Finite Element Method but also integrates component measurements which are necessary to solve the optimization problem. The efficiency of the method is illustrated through the assembly of a sliding door of a helicopter.
Keywords: Flexible part, assembly, simulation, deformation.

1. INTRODUCTION

Compliant sheet metal assembly is a process widely used in automotive or aerospace industry **[Camelio et al., 2003]**. Part compliance enables the assembly but it also causes considerable variations that will influence the final geometry of the assembly. Many works have addressed the problem of assembly simulation of flexible parts. Hu and Camelio **[Hu et al, 2006]** have summarized the recent developments of simulation models for compliant assembly and present the applications of such models. Most applications concern the simulation of assembly variations integrating part and fixture variations. Works are related to assembly by spot welding and are based on the PCFR cycle (Place, Clamp, Fasten and Release) **[Chang et al., 1997], [Chang et al., 1999], [Dahlström et al., 2005], [Hu et al., 2001]**. All the methods rely on the use of Finite Element Method (FEM) to calculate deformation after assembly. Liu and Hu **[Liu et al, 1997]** have first introduced the notion of sensitivity matrix which establishes the linear relationship between the incoming part deviation and the output assembly deviation. Some authors propose to also integrate variations induced by the tooling **[Chang et al., 1997], [Camelio et al., 2003]**. **[Long et al., 1997]** consider the gap between parts and fixtures into the assembly modelling. **[Lian et al., 1999]** analyse the causes of variations by using a statistical method. Most of these works are linked to the automobile industry.

Some recent works focus on the optimization of part positioning in order to respect assembly tolerances while taking into account part variations. **[Cid et al., 2005]** propose a best assembly process that takes into account through simulation the flexibility of components. The method, which is based on the influence of component geometrical variations on functional conditions, determines the coefficients of influence in a symbolic writing and used them during the optimization which leads to an efficient simulation loop. The method is particularly efficient for compliant assemblies with more fitting liaisons than necessary which introduce over-constraints, deformations and stresses that have to be managed **[Chevassus et al, 2006]**.

Anyway, the proposed approach supposes that the component geometry is measured at each stage of the process. Therefore, the method presented in the paper resumes the previous works and integrates part measurement to initialise the method. The assembly studied consists of one flexible part which is set in position thanks to linkage devices on rigid parts (figure1). The aim of the paper is to propose a simulation method leading to the optimal fitting values of these linkage devices so that functional requirements of the assembly are ensured. After a short presentation of the method and its key points, an illustration based on an industrial case is exposed.

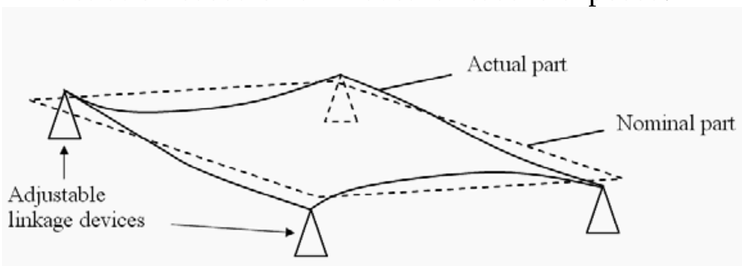

Figure 1; Assembly of a flexible part with adjustable linkage devices.

2. METHOD FOR ASSEMBLY SIMULATION

The assembly and setting process is carried out according to the following four steps:

- Initial component assembly with geometrical deviations and default settings
- Assembly measurement on predefined interface points
- Simulation and best fit optimization which leads to determine the fitting values of linkage devices
- Application of the optimized fitting values and checking of the assembly constraints

The next section details the method for assembly simulation associated to the process described above.

2.1. The Approach

The simulation of the compliant assembly relies on the method exposed in **[Cid et al., 2004]**. This method supposes that the behaviour of the flexible part is linear and only considers small displacements. Using the Finite Element Method (FEM), the displacements of each point of a component are linked to the forces by the matrix K:

F=K.U

This equation is equivalent to the following one:

$$\begin{bmatrix} K & -I \end{bmatrix} \begin{bmatrix} U \\ F \end{bmatrix} = \begin{bmatrix} 0 \end{bmatrix} \quad (1)$$

Formally, we can impose forces or displacements values at each point which leads to the boundary conditions. The writing of all the boundary conditions yields to:

$$\begin{bmatrix} K \quad -I \\ BoundaryConditions \end{bmatrix} \begin{bmatrix} U \\ F \end{bmatrix} = \begin{bmatrix} 0 \\ S_{BC} \end{bmatrix} \quad (2)$$

Solving Equation 2 leads to the values of forces and displacements at each point of the components. However, the simulation provides the flexible component deviations relative to the rigid body. As a result, the displacement U is not expressed relatively to the nominal geometry but is expressed relatively to the rigid frame. As the problem is linear, displacements and forces can be written as follow:

$$\begin{cases} U = U_{def} + U_{fit} \\ F = F_{def} + F_{fit} \end{cases} \quad (3)$$

Where U_{def} and F_{def} are the initial deviations and forces of the assembly and U_{fit} and F_{fit} are the deviations and forces induced by the fittings.

Basically, the method consists in optimizing the values of U_{fit} so that functional requirements are respected. Once U_{fit} are optimized, the values of F_{fit} obtained using equation 2 must be compared to admissible mechanical constraints. The main problem is the determination of the reference state (or initial state) of the assembly in order to identify U_{def} and F_{def}. The next section is dedicated to this point.

2.2. Initial state measurement

The originality of the method is to identify the geometry of the reference state through the measurement of the assembly. The component is set in its over-constrained use position. Only sampled points are measured on the component, and the measured deviations correspond to the actual shape of the component and the initial values of the fittings. The whole geometry is evaluated through the FEM method considering measurements as boundary conditions.

On the other hand, the determination of the values of F_{def} requires the knowledge of the free-state of the assembly (figure 2). To determine the free state of the assembly, the flexible part must be set in a properly-constrained position. Significant points are thus measured. The difference between the reference state and the free-state gives the value of U_{def}:

$$U_{def} = U_{ref} - U_0 \quad (4)$$

F_{def} is afterwards calculated using equation 2.

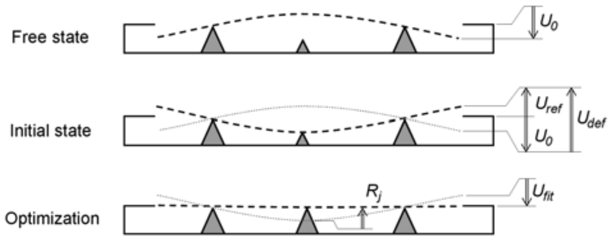

Figure 2, Geometrical deviation in the assembly.

2.3. Optimization of the fittings

By imposing the fitting values as boundary conditions, equation (2) yields to:

$$\begin{cases} U_{i\ fit} = u_{i0} + \sum_{j=1}^{n} a_{ij} R_j \\ F_{i\ fit} = f_{i0} + \sum_{j=1}^{n} b_{ij} R_j \end{cases} \quad (5)$$

Where u_{i0}, f_{i0} are constants, R_j is the j fitting value (j=[1;n]), and a_{ij}, b_{ij} are the influence coefficients of the "j fitting" at the node i. Using equation (3) this gives:

$$\begin{cases} U_{i} = u_{i0}^{*} + \sum_{j=1}^{n} a_{ij} R_j \\ F_{i} = f_{i0}^{*} + \sum_{j=1}^{n} b_{ij} R_j \end{cases} \quad (6)$$

As assembly conditions C_q are expressed using U_i, they can be expressed in function of the R_j values:

$$C_q = c_{q0} + \sum_{j=1}^{n} c_{qj} R_j \,, q = [1; p] \quad (7)$$

The optimization of the fitting values can thus be performed in order to respect the assembly functional requirements.

3. STUDY CASE

The proposed method is illustrated through an aeronautic example which consists in assembling the sliding door of Dauphin helicopter. This composite door must satisfy functioning conditions as well as waterproof qualities, aerodynamic and safety constraints. The kinematics of the door is based on four positioning hinges that slide on three curved rails. The hinges are equipped with different settings which enable to reach a perfect fit (figure 3). The subject of the study is the door assembly when it is in closed position.

3.1. Description of the system

The kinematics of the door is based on four positioning hinges that slide on three curved rails (figure 3). These hinges, which also position the door when it is closed, can be adjusted in the x, y and z directions for the front hinges and in the z direction for the back ones.

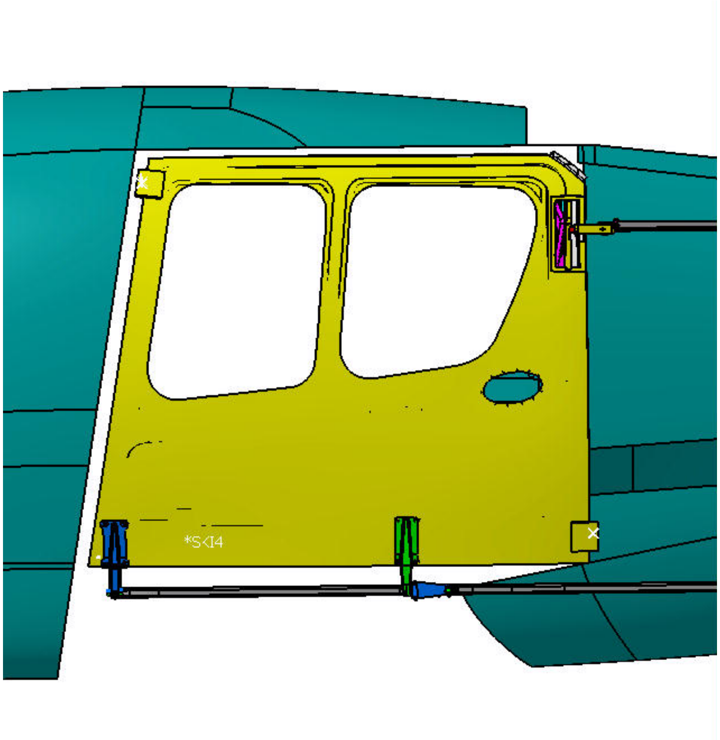

Figure 3, Door linkage devices.

Three other devices are used to lock the door, and can be adjusted in the x, y and z directions. Moreover, all along the door edge, a seal ensures the airtightness between the structure and the door.

3.2. Assembly constraints

The door assembly must satisfy some constraints given by the functional requirements:

- Security,
- Aerodynamics,
- Airtightness.

Among all these constraints, only those which influence the fitting of the door onto the structure are retained.

The analysis of these constraints shows that some fitting directions are influence free on the door assembly. Consequently, these fitting directions are not taken into account in the optimization process.

3.3. Determination of the fitting of linkage devices

The problem is formally written from equation (1) to equation (6) using Mathematica®. On the other hand, the optimization of the fitting is programmed using Matlab®. Results are presented through a graphic interface which is divided in four parts, each one corresponding to a step of the method. The first graph (Top-Left) presents the mesh of the door as well as the measurement points. All the measurement points are located all along the edge of the door.

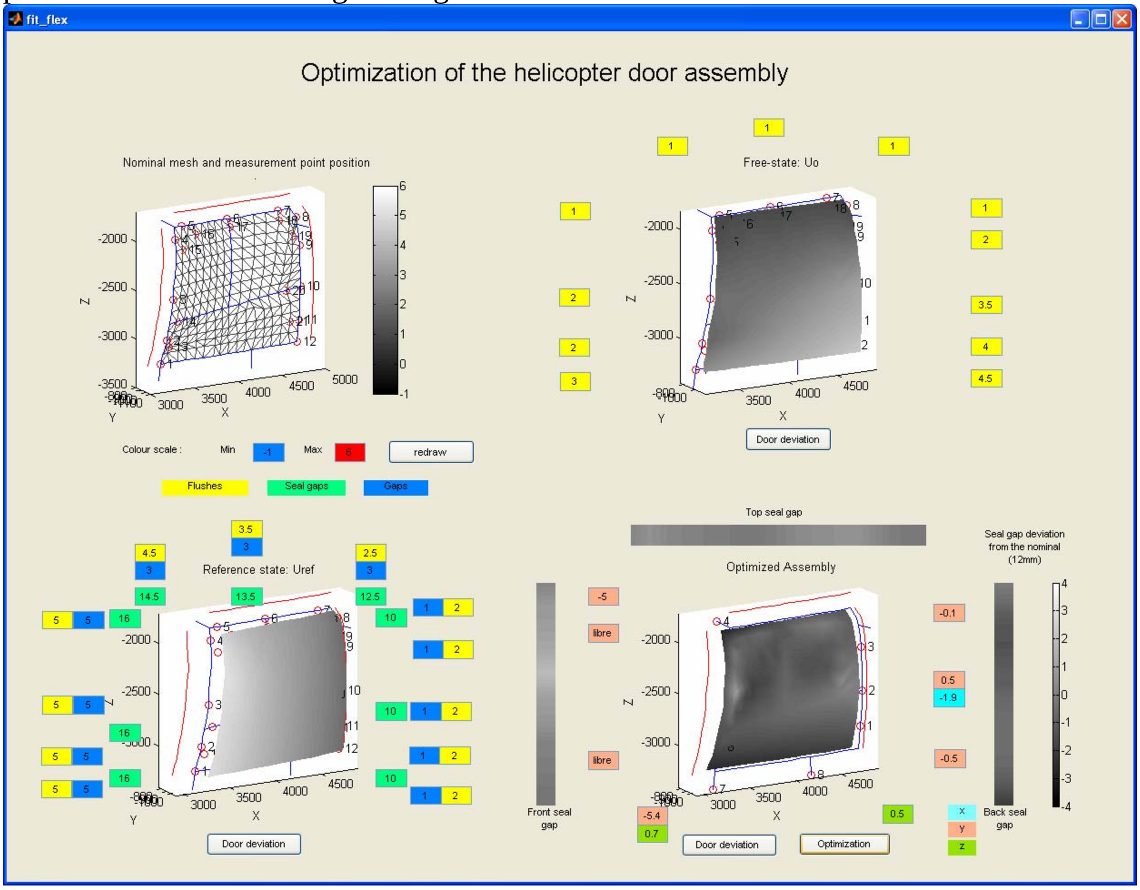

Figure 4, Fitting window for the helicopter door.

The second graph (Top-right) corresponds to the free-state. The free-state is obtained by the measurement of the flush values when the door is set in a properly-constraint position onto the helicopter structure.

The third graph (Bottom-Left) is the reference-state: the door is assembled in its actual position. Flushes, gaps and seal gaps are measured and defined the initial values of the geometrical parameters. The initial values of the forces are obtained using the FEM considering the displacements between the reference-state and the free-state as boundary conditions.

Therefore, initial data (geometrical parameters and forces) are known, and the optimization can be carried out. The fitting values of the linkage devices after optimization are indicated in the boxes around the fourth graph (Bottom-Right).

4. CONCLUSION

In this paper, a measurement based assembly approach is proposed which takes into account the measured geometries of components to be assembled as well the deformations of one of them. The method has been applied on the simulation of assembly of a helicopter door with promising results (figure 4). In particular, the proposed approach would allow gains of time for the assembly process. Currently the method suggested works only on assemblies with only one flexible part. Further work will thus consist in extending this work to assemblies with several flexible parts.

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