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Variation analysis of automated wing box assembly

Otto J Bakker[a,*], Atanas A Popov[a], Svetan M Ratchev[a]

[a]*Advanced Manufacturing Technology Research Group, Faculty of Engineering, University of Nottingham, University Park Campus, Nottingham, NG7 2RD, UK*

[*] Corresponding author. Tel.: +44 (0)115 74 86132; fax: +44 (0)115 95 13800. *E-mail address:* OttoJan.Bakker@Nottingham.ac.uk

Abstract

Manufacturing process variability is a major issue of concern in high value industries. Manufacturing small batches and in some cases batches of one is a very expensive process with specific requirements for manufacturing operations, tooling and fixturing and their level of automation and informatics provision. The automation targets cost reduction and a counterbalancing of the ever lower numbers of skilled shop floor workers. However, these small series typically are products that contain complex and compliant parts, and often also a high number of parts and components. The automation of this type of low-volume high-value production can be a daunting task.

Each process has its own key parameters that are required to be within a certain tolerance band in order to ensure product quality, such as e.g. the dimensions and location of assembly mating features. Dimensional quality assurance is typically done with in-process measurement, or the measurement of certain key characteristics (KCs) in the current setup, but a special setup may have to be used in a measurement-only step in the manufacturing process. Each manufacturing stage introduces errors stemming from uncertainties in the fixturing, used processes etc. These errors will propagate in downstream stages and can even worsen errors introduced in the latter stages.

The paper presents a new generic methodology for the use of stream of variation (SoV) analysis within a Smart Factory environment such as the Evolvable Assembly Systems (EAS) framework. The research is demonstrated using a simplified case study of one of EAS demonstrators for an aircraft wing box assembly. The wing box assembly and its KCs are described using formal representation. The SoV model is applied to model and simulate the assembly process. The simulation results are then analysed to predict, control and minimise the error propagation coming from uncertainties in process and equipment.

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Keywords: Variation analysis; aerospace manufacture; multistage assembly process

1. Introduction

The variability in manufacturing process outcome is a major issue of concern in the aerospace industries. Today's markets are characterized by high fluctuations in demand and a high level of customization, resulting in the manufacturing of small batches and even one offs. In addition, aerospace components are relatively large, yet have very low dimensional tolerances, making the dimension to tolerance ratio larger than most mechanical assemblies. In addition, individual parts are made as light as possible and therefore are very compliant. It requires a large number of fixtures to keep all the components and subassemblies in shape, until after the entire aircraft is assembled, which is remarkably stiff [1]. Something similar holds for the automotive industry, since cars are for a large degree made of sheet-metal sub-assemblies, which are also highly compliant until the entire assembly is carried out [1,2]. Apart from the production volume, aerospace assembly differs from automotive assembly in one important aspect: for a number of reasons it is considered best to have aircraft components fastened by rivets or bolts. This requires the drilling of tens or hundreds of thousands of holes. Due to lightning strike and structural requirements these holes cannot be too large, thus tightening the tolerances. This makes part-to-part assembly problematic, however the application of part-to-part assembly would introduce large cost and other technical benefits to aerospace manufacturers.

For this reason, the study of variations in aerospace manufacture and assembly has received specific attention from the research community, e.g. [3–7]. Maropoulos *et al.* [5] have developed a metrology assisted assembly method. Bakker *et al.* [6] studied the reclamation of a trailing edge hinge line key characteristic (KC) using a reconfigurable fixture and Vaughan *et al.* [7] studied the use of a variation aware algorithm for the placement of ribs in an aircraft wing-box assembly. In the automotive sector, two more formal approaches to assembly can be found, and are written up in two monographs. The first is called Stream-of-Variation (SoV) [2]. This approach concerns fixturing errors for 2D assemblies, the largest source of error in automotive industry [2]. The other approach is named state-transition models [1], and mostly studies variation in part dimensions. Applying constraint equations, Huang *et al.* [8,9] have extended SoV to 3D and also to incorporate errors coming from variation in part dimensions. Apart from a few exceptions, these methods are not widely applied to study aerospace assem-

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bly, see e.g. [10,11]. However, using more formalised forms of description and modelling of aerospace assemblies would unlock the benefits of recent advances in the application cyber-physical systems in automation. This papers seeks to formalise a state-space description for aerospace assembly, with as specific case study the structural assembly of a wing-box.

The paper is organized as follows. In the Methodology section, firstly the an assembly method and an improvement are discussed in Section 2.1. Subsequently the assembly KCs are studied in Section 2.2. The majority of the Methodology section is devoted to the establishing of the stream-of-variation model in state-space notation, this can be found in Section 2.3. Furthermore, the modelling of the shimming process that ensures that top and bottom panels are assembled according to specification is done in Section 2.4. The simulation and results are discussed in Section 3. Conclusions, observations and intended extension of the work are given in Section 4.

2. Methodology

2.1. Assembly methods

2.1.1. Assembly strategy 1

In order to establish the stream of variation model, firstly the assembly methods need to be discussed. Typically, a wing-box assembly starts with building the trailing edge (TE) sub-assembly. From there the TE spar is mounted on the TE sub-assembly. The next steps are adding the ribs and the leading edge (LE). After this, the panels at the top and bottom sides of the wing-box are mounted to the TE spar-rib-LE spar assembly. In the model analyzed in this work, the specific order can be seen in Fig. 2. N.B. this and the other assembly strategy are two possible assembly sequences, and do not necessarily form best-practice, or express the view of the authors on assembly strategies. In the figure the approximate location of the primary and secondary locating points for the assembly are drawn as the concentric circles (pin-hole) and the pin-slot respectively. In the first station the TE spar and the rib attachment angle are assembled together. The locating and measurement points for all the parts in the assembly can been seen in Fig. 1 and the numerical values for each of these points are given in Table 1. In Station 1 P_1 and P_2 are used to hold the TE spar, and P_3 and P_4 are used to rib attachment angle.

Going to Station 2, the TE spar-rib attachment angle sub-assembly is held by P_1 and P_1, as can be seen in Fig. 2 and rib is held by P_9 and P_{10}. At this station, the rib is assembled to the TE spar-rib attachment angle sub-assembly. Parallel to this the other rib attachment angle, held by P_7 and P_8 is assembled onto the LE spar held by P_5 and P_6, which are the main locating points for this sub-assembly.

At the third station, the second sub-assembly held by locating points P_5 and P_6 is mounted onto the main sub-assembly, held by P_1 and P_2.

At the fourth station, the sub-assembly is held for measurement by P_1 and P_6. For this station there is an output matrix **C**. The output matrix relates the deviations of the measured points to the deviated states. Based on these measurements, shims are made and attached on the top and the bottom of the TE spar-rib-LE spar sub-assembly.

In Station 5 and 6, the top and bottom skin, respectively part 6 and 7 in Fig. 1 are mounted on the TE spar-rib-LE spar sub-assembly, held by locating points P_1 and P_6 (Note that the outward normal of the bottom skin points in positive z-direction and the outward normal of the top skin points in negative z-direction in Fig. 1.)

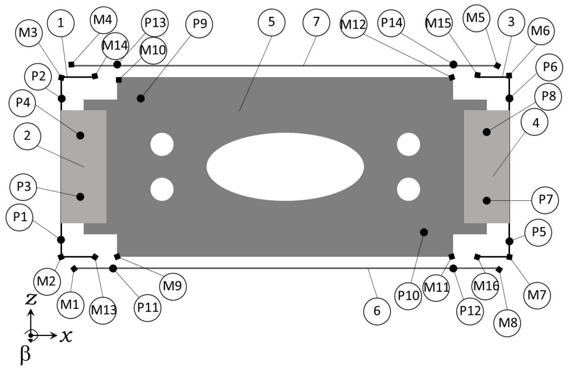

Fig. 1. Simplified cross sectional model of a wing-box assembly, N.B. stringers, clips and cut-outs in the rib to accommodate for the stringers are omitted to simplify the drawing and some of the calculations. P_i is locating point i, M_i is measurement point i. Parts are: (1) trailing edge spar, (2) rib attachment angle, (3) leading edge spar, (4) rib attachment angle (5) rib, (6) top skin (panel) 7 bottom skin (panel).

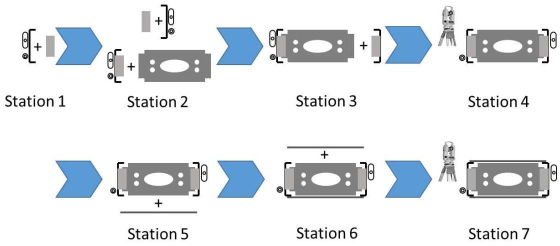

Fig. 2. Assembly sequence of the wing-box cross-section using assembly strategy 1.

At the 7th station, the whole wing-box assembly is held for measurement by P_1 and P_6. At this station the gaps between the panels at the top and bottom side of the wing-box is measured.

2.1.2. Assembly strategy 2

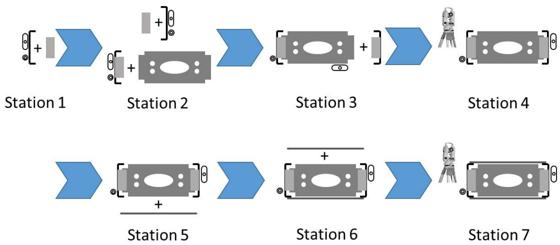

Fig. 3. Assembly sequence of the wing-box cross-section using assembly strategy 2.

As can be seen in Fig. 3, assembly strategy 2 is very similar to assembly strategy 1, with the difference that in Station 3, the secondary locating point is moved from the TE spar to the