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Variation simulation for composite parts and assemblies including variation in fiber orientation and thickness

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Abstract

All manufacturing processes are afflicted by geometrical variation, which can lead to defect products. A simulation tool for geometry assurance analysis is therefore important in the design process. The use of composites has recently increased drastically, but there is still a lack of understanding about the effects of variation in such parts. A method for predicting variation in subassemblies, including variation in fiber orientation and ply thickness for composites is presented. The approach is demonstrated on an industrial case and finite element analysis is used to calculate the deformation. In particular, contribution from variation in material properties to the variation in critical points is analyzed. The results indicate that material uncertainties have a small impact on the geometric variation for the test case.

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1. Introduction

Composites and other high technology lightweight materials are becoming more common in many areas of production and manufacturing such as e.g. the aviation and automotive industries. This is due to the many beneficial properties of composites over traditional materials, e.g. weight reduction with retained strength and stiffness, corrosion resistance, thermal properties, fatigue life and wear resistance. The lower weight leads in turn to reduced fuel cost and carbon dioxide emissions. Almost all vehicles benefit from switching to composite materials. For example half of the Airbus A350 and the Boeing 787 aircrafts consist of composite materials. However knowledge about detailed behaviour of lightweight materials is still insufficient.

For composites, there might be variation in material and process related parameters, such as thickness and fiber orientation. In this paper, the influence of those on the level of geometrical variation in a subassembly is investigated. To do this, methods for variation simulation are used. An overview of variation simulation is given in Section 1.1 and an introduction to composite materials and manufacturing is given in Section 1.2. In Section 1.3 the finite element (FEM) model used for the composites is described. The industrial test case is described in Section 3 and the method used in Section 4. In Section 5 the results are discussed and Section 6 contains the conclusions.

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Background

1.1. Geometry assurance and variation simulation

Geometry assurance is a term used to gather a lot of activities aimed at securing the geometrical quality of the final assembled product. Sources of geometrical variation in a subassembly are mainly variation in shape and size of single parts and variation in the assembly process. The level of geometrical variation in the assembly is also dependent on the robustness of the design concept. A robust design concept is insensitive to variation and can suppress the effects of the sources of variation [1]. The main key to making a physical assembly geometrically robust is to find robust locating schemes. A locating scheme fixates the part in space during manufacturing and joining operations and control how variation propagates in the assembly. An overview of different locating schemes is given in [2].

In order to predict the level of geometrical variation in a subassembly or a final product, Monte Carlo based software for variation simulation is often used. The parts in a variation simulation can be modeled as rigid or non-rigid parts. Direct Monte Carlo simulation, combined with finite element analysis (FEA), is a standard technique for variation simulation of non-rigid parts. However, since a large number of runs are required to achieve satisfactory accuracy, the method is very time-consuming if a new FEA calculation is executed in each run. Liu and Hu [3] presented a technique called Method of Influence Coefficients (MIC) to overcome this drawback. The main idea of their method is to find a linear relationship between part deviations and assembly spring-back deviations. A sensitivity matrix, constructed using FEA, describes that linear relationship. This sensitivity matrix is then used in the simulations, and a large number of FEA calculations can be spared. The validity of the method was shown by Camelio et al. [4], who applied it to a multi-station system. MIC can also be combined with contact modelling [5]. Contact modelling is a way to hinder parts to penetrate each other virtually. Wärmefjord et al. [6] developed contact modelling for variation simulations further and showed its importance on an industrial case study.

There are several commercial software for variation simulation, such as 3DCS [7], VSA [8] and RD&T [9]. In the work described in this paper RD&T is used. RD&T is a commercial software but is also used as a workbench for research within the area of geometry assurance and non-rigid variation simulation. In RD&T, a Monte Carlo-based statistical variation simulation is conducted in order to analyze the tolerance stack up and to predict the geometrical variation in the final assembly. A total sensitivity matrix is implicitly defined in a FEA-based simulation model describing all mating conditions, kinematic relations and non-rigid behaviour.

1.2. Composites

Generally composites are materials consisting of a composition of two or more different components. The most common are made of two materials, a matrix material and some kind of reinforcement to increase strength and stiffness. Basically there are three kinds of composites, fibrous, particulate and laminated. Fibrous composites consist of fibers in one material inside a matrix in another material. Particulate composites are macro sized particles inside a matrix material. Finally laminated composites are made of plies of different materials. The plies can be either of the two first kinds of composites as well as any other material.

Common to all composites with continuous fiber reinforcement is that they will have highly anisotropic behavior being much stronger along the direction of the fibers. This enables a precise design of laminated composites with fibrous composite plies having different orientations according to where the strength is needed. More detailed information on composites can e.g. be found in [10] and [11].

There are several composite manufacturing processes, hand lay-up, resin transfer moulding (RTM), automated tape laying (ATL) and automated fiber placement (AFP) to mention some of the most common ones. In the hand lay-up process, the composite plies or the fiber mats that will constitute the laminate are placed as a dry stack in a mould, then the resin that will constitute the matrix are impregnated into the fibers using rollers or brushes. Then the laminate is left to cure in room temperature or in an oven. The RTM process is similar to the hand lay-up with the difference that another mould tool is placed on top of the dry stack of fibers forming a cavity where the resin is then injected. There can also be vacuum in the cavity to help the resin being drawn into the fabrics. Hand lay-up and RTM are methods typically used for smaller more complex components and the quality of the finished product is dependent on the skills of the laminators.

ATL and AFP are both, as the name suggests, highly automated processes. In ATL a preimpregnated tape with fibers are placed by a robot in rows next to and across each other in specific directions over a large surface. AFP works in the same way, but single fiber tows are placed instead of a tape. These two methods can handle parts with holes as well as parts with varying thickness and number of plies in different areas. Further ATL and AFP are widely used in production of large aircraft structures such as wings skins, spars and stringers. More about composite manufacturing can be found in e.g. [10] or [12].

In the finished composite part there are several structural uncertainties and defects. For example resin-rich (i.e. fiber-poor) regions, voids, microcracks, delamination, variation in fiber alignment and thickness [10]. Several studies have been done about the effects of one or more of these defects, see e.g. [13], [14], [15], and [16]. The purpose of this work is to investigate whether uncertainties in fiber orientation and ply thicknesses affect the level of geometrical variation in a final subassembly.

1.3. Finite element method for composite shells

For the variation simulations of non-rigid parts, a finite element shell model is used. The formulation is based on the theory developed by Simo & Fox in [17], for smooth structures, and extended by Ibrahimbegovic in [18] to non-