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Early Design Verification of Complex Assemblies using a Hybrid – Model Based and Physical Testing - Methodology

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Design verification in the digital domain, using model-based principles, is a key research objective to address the industrial requirement for reduced physical testing and prototyping. For complex assemblies, the verification of the design intent and the associated production methods is currently fragmented, prolonged and sub-optimal, as it is based on the sequential consideration of various aspects in the digital and physical domains using a range of systems. This paper describes a novel hybrid design verification methodology that integrates model-based verification analysis with the measurement data and plans derived from the physical testing of prototype assemblies, in order to facilitate the early verification of complex designs from the perspective of satisfying key assembly criteria.

Design; Design Method; Assembly; Measurement; Tolerancing

1. Design verification of complex assemblies

Although the early design phases are identified as offering the best opportunity to enhance the performance of the new product or process, it is difficult or impossible to consider key functional or production aspects due to the fact that limited information is typically available at these stages. This is especially the case for complex aerospace and defence products that have prolonged development cycles, characterised by engineering changes and the evolution of functional and production performance criteria.
Digital Mock-Up (DMU) is emerging as a core design collaboration tool in these industries, around which different engineering teams work to verify the product through its entire life cycle [1]. Design for Manufacture and Assembly (DFMA) is a frequently used set of methods deployed within DMU to improve the way production and assembly processes are executed [2]. It must be remembered that DMU simplifies the real artefacts and processes as digital mock-up technology does not simulate the impacts of all sources of assembly variation. Consequently, digital simulation results can deviate significantly from the real assembly [3]. There are many new technologies for complex product assembly [4] ranging from digital modelling tools for assembly variation propagating modelling and analysis [5] and new manufacturing technology concepts that include Measurement Assisted Assembly (MAA), Predictive Shimming, and Automated Wing Drilling Equipment (AWDE). These techniques improve assembly operations by simulating component mating using tolerance analysis techniques and offer considerable benefits to complex assembly environments, such as aero-structure assembly [3, 6].

Industry still requires the development of new ways of verifying complex products and assemblies [7, 8] in an integrated manner, from the digital domain and into the physical prototyping stages. This paper reports on a new hybrid methodology that integrates model-based analysis with physical measurement plans and data in order to facilitate the early verification of complex designs from the perspective of satisfying key assembly criteria. The methodology is exploited in a realistic complexity case study that demonstrates how tolerances can be managed more efficiently within an aircraft structure so that the assembly key characteristics can be maintained or improved while component tolerances are relaxed and interface management considerations are minimised using MAA techniques.

2. A new Hybrid – Model Based and Physical Testing – Design Verification Methodology

2.1. Component and assembly level verification

The design of aerospace structures is shown in Figure 1. It starts with the design of a prototype that is tested for its ability to meet the functional requirements. Initially, prototype tolerances and design specifications are decided on the basis of past experience to derive product key characteristics (PKCs). At this stage, structure datums are allocated using GD&T, which are considered in designing assembly jigs and fixtures. This is then followed by specifying component level tolerances which define the manufacturing key characteristics (MKCs). The MKCs represent manufacturing process parameters that can significantly affect PKCs. Often, for new manufacturing concepts, manufacturing process capability data is either non-existent or very hard to obtain [9]. MAA processes are highly applicable in such situations to provide real time enhancement of process capability. However, the assembly and measurement planning for the deployment of MAA techniques may be hampered by the limited availability of data during early design. Key planning aspects include the identification and sequencing of the assembly stages together with the selection of corresponding measurement systems, the definition of methods to verify MKCs and the calculation of measurement uncertainty at each stage [3].

Aspects of variation propagation through designed tolerances in single and multi stage, compliant assembly have been researched [10, 11], where dimensional variation has been modelled using statistical and mathematical techniques and there are digital modelling tools available today and deployed in industry to carry out a range of tasks including; tolerance specification, analysis, synthesis, process description, sensitivity analysis and interfacing of tolerancing with measurement and inspection systems. Yet, several functions are fragmented as tolerances assigned in the design phase cannot be verified and revised instantly and needs to be processed sequentially. Furthermore, when designed tolerances are achieved through measurement assisted techniques, simulated variability needs to be compared against the measured variability. Also, measurement systems for verification generate multiple representations of the product structure and these data-rich spatial representations need to be referenced against the core product model in order to allow for the traceability of the corrective measures taken while prototype manufacture.

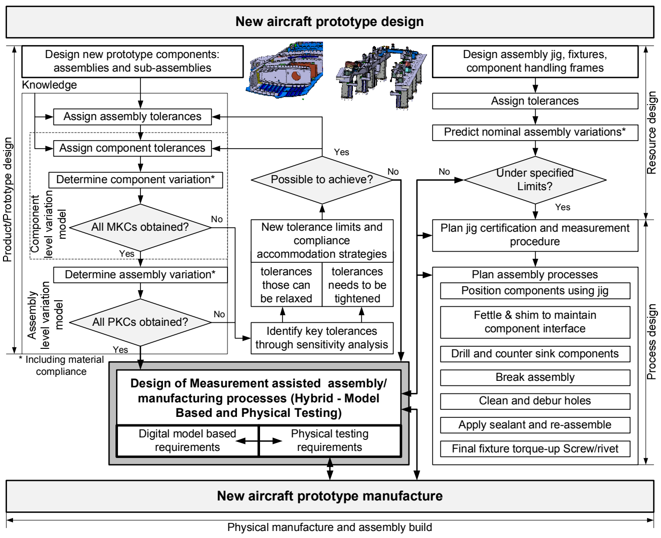

Figure 1. The role of Measurement Assisted Assembly in integrating design of product and assembly system for aerospace structures.

2.2. Assembly jig, tooling and fixture design and verification

Assembly resources such as jigs, tools, fixtures and material handling frames are designed and manufactured to realise the designed prototype. Traditionally, the positional, dimensional and geometric accuracy of the assembly is derived indirectly from the assembly tooling. That is to say, if the tooling is correct and the components are positioned correctly within the tooling, then the assembly is correct. This is a major cause of quality issues arriving from the lack of product model based process control and is addressed by the new generation of MAA processes. Measurement assisted processes ensure designed tolerances are maintained. However, in order to achieve this, a hybrid, model based and physical testing verification process needs to be incorporated to maintain the required tolerances within the tooling and the assembly process.

Figure 1 shows the two new modules namely, “Digital model based verification” and “Physical testing based verification” that underpin the proposed hybrid, design verification methodology. The Hybrid - Digital Model and Physical Testing Based - Verification Methodology includes the following functions; i) simulate assembly variability by considering tolerances specified on the product and the assembly jigs, ii) identify the key tolerances responsible for impacting the assembly characteristics, iii) identify component and assembly level measurement stages and mandatory inspection points required to maintain the key assembly characteristics, iv) incorporate component and assembly measurement data for planning subsequent assembly processes, and v) reconfigure assembly processes depending upon the analysis of measurement data. This creates a coherent digital environment in which design, tooling and metrology information can be utilised to design, reconfigure and sequence prototype assembly processes.

3. Digital model based verification functions

The digital model based verification requirements arise from the main constituent elements of assembly structure variability, which can be classified as: (1) variation through discrete datums and tolerance stack-up, fastening techniques and compliance; (2) dimensional uncertainty in auxiliary assembly processes such as measurement and machining, as shown in Figure 2.

3.1. Variation through discrete datums and tolerances stack-up

The goal of this model based verification requirement is to simulate the effects of component and assembly level tolerances on the overall assembly variability by disintegrating the geometric tolerances into positional vectors for identifying the axial and planar deviation fields applicable to any point of interest in the assembly structure. Thus, the effects of designed geometric tolerances at component level can be understood, key tolerances can be identified, and decisions can be taken regarding the manufacturing processes to adjust those key tolerances. This understanding is gained by constructing a Monte Carlo based Finite Elements Analysis simulations of variability in compliant assemblies.

3.2. Effect of material compliance and fastening techniques

Modelling of the compliant nature of sheet metal body parts has been undertaken in the automotive industry for designing and planning production resources (locators, clamps, supporting elements and assembly jigs) in such a way that key product characteristics can be achieved. For aerospace structure assembly the models need to consider the dynamic, nonlinear and anisotropic behaviour of state-of-the-art composite materials. Limited research exists today focusing on the fastening and joining features for composite structures due to the fact that such intricate geometries are often neglected in FEA studies while considering the generalised stiffness of the overall structure.

Using the forms of typical aerospace structural joints, the research considered the key factors influencing the compliance of the joint features in the model based verification requirements.

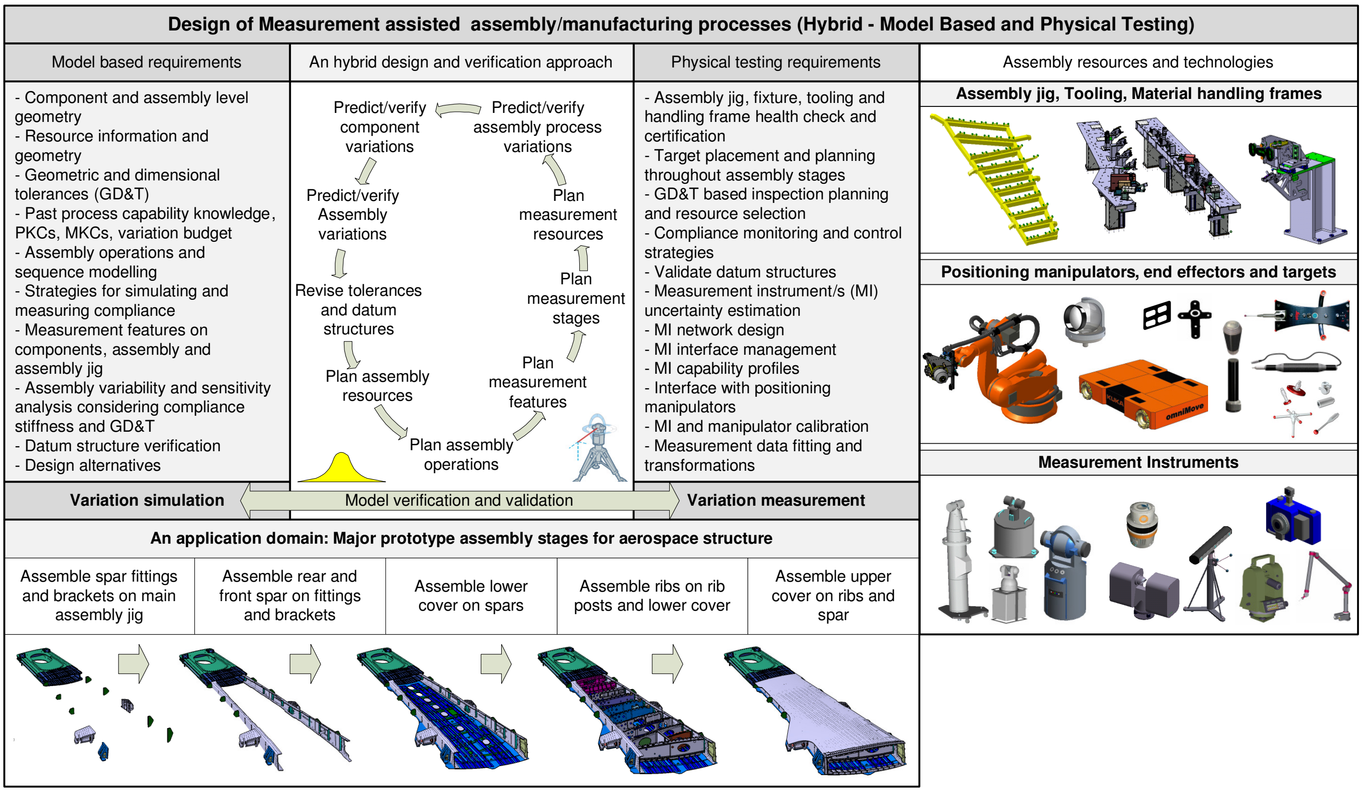

Figure 2. Structure of the Hybrid - Digital Model and Physical Testing Based - Verification Methodology for Complex Product Design

The design verification objective was to obtain the joining pressure distribution and to estimate the stiffness of the joined components within the assembly interface. The inputs for this simulation analysis are: the geometry and stiffness of the assembly interfaces of the components to be joined, the bolt/rivet-map with unit bolt dimensions, preload and clamping conditions; and the clearance between the bolt/rivet shank and the joint hole.

3.3. Effects of auxiliary assembly processes

In addition to the effects of tolerances on assembly variability, another important factor addressed in the methodology described herein is the effect of assembly processes on assembly variability. For example, measurement assisted fettling of rib feet is done before assembling the upper cover on to spars and ribs in a jig assembly. Thus, in addition to component tolerances, assembly results are influenced by these auxiliary measurement, machining and fabrication processes. The dimensional uncertainty of these processes has to be considered while estimating assembly variability of the aircraft structure.
Current state-of-the-art methods for modelling variation propagation in assembly can only deal with relatively simple assembly processes of well known process capability. This is not the case for aerospace assembly, hence the assembly variability model needs to be derived by modelling the measurement assisted assembly process. One of the key tasks of the developed methodology was to build a systematic assembly process library which can be used to model the overall assembly process using modular auxiliary processes. The overall assembly process can be broken down into a series of modular processes to estimate the resultant dimensional variation in the assembly structure.

4. Physical testing verification functions

Assembly variation and uncertainty propagation begins with the commissioning of the tools and fixtures. The combined tolerance of the fixture, location pins, slips and facility tooling must be less than the assembly tolerances; ideally <10% of the tolerance level, although this is rarely possible. Assembly fixtures can have global tolerances of around 0.15mm over 15-30m, consuming a large proportion of the assembly tolerance budget. Additionally, the fixture must be commissioned with an accuracy that is an order of magnitude better than the fixture's build tolerance. The measurement uncertainty and tolerances associated with building the fixture result in using tight tolerances during the design process.
There are several ways of carrying out physical testing in terms of dimensional and shape verification including, direct or indirect measurements, and measuring either all the parts (100% inspection) or a selection of parts [3, 12]. The environmental conditions - average temperature, temperature gradients, pressure, humidity and carbon dioxide content - that are present during factory production greatly influence the performance of measurement systems deployed for structure verification and measurement assisted assembly [3]. As measurement uncertainty needs to be an order of magnitude smaller than the level of the design tolerances, it is important to accurately model measurement uncertainty in industrial measurement processes, especially for large volume applications. Measurement uncertainty is reduced by networking measurement instruments together; measuring points from multiple positions enables optimisation algorithms to be employed, this reduces the associated point uncertainties to a level of less than 50µm (at 3σ). This high accuracy constellation of points becomes a datum structure for subsequent measurements, both for verification and

build purposes. Networking systems also overcomes the line-of-sight issue associated with verifying complex fixture geometries. During variation analysis, using the hybrid model described in Figure 2, measurement uncertainty can be used instead of nominal build tolerances and this reduces the model variation. The measurement process, instrument placement and measurement uncertainty can be simulated to model variation using MAA methods.

5. Implementation and testing via a case study

5.1. Assembly tolerancing analysis case study objectives

The study was part of a major transnational aerospace project focusing on advanced aircraft structures. The specific objective of the case study included understanding of how metrology data from the wingbox build process could be used to; (i) determine whether discrete components meet their GD&T specifications, (ii) plan the measurement processes for verification, and (iii) predict the final assembly dimensions.
This tolerance analysis case study used state of the art software and systems to simulate and measure assembly variation. Dimensional tolerances were considered as a primary source of assembly variation at the initial design stage. Required tolerances in the simulation were selected form part specifications and condition of supply (COS) documents. A hybrid approach has been followed in the analysis, where a simulation model was developed to address the model based verification requirements and then it was followed (as shown in Figure 1) by the physical, in-process assembly measurement data to reduce simulation uncertainty while considering measurement assisted assembly processes. Numerous assembly processes involved in building the pilot wing box were simulated using the software. The results of the simulation defined how well these assembly processes can be modelled using this software. The assumptions made while modelling such assembly processes were revised to establish a common agreement between simulation outcome and metrology data. Hence, these assumptions can be utilised in the future course for accurately predicting outcomes of consequent assembly build stages and new build philosophies.

5.2. Methodology exploitation for assembly planning decisions

The variation simulation requires as inputs the nominal form of components, the variability of components and the assembly process. It then outputs the overall form and variability of the complete assembly. This allows sensitivity studies to show to what extent individual component tolerances contribute to the overall PKCs. Different build sequences can be compared to show how they affect the overall assembly variability, as shown in Figure 3. Both component verification and variation modelling have been carried out with respect to the pilot wing box Key Characteristics (the PKC's) which were, in general, the aerodynamic profile and the gaps between major structural components.

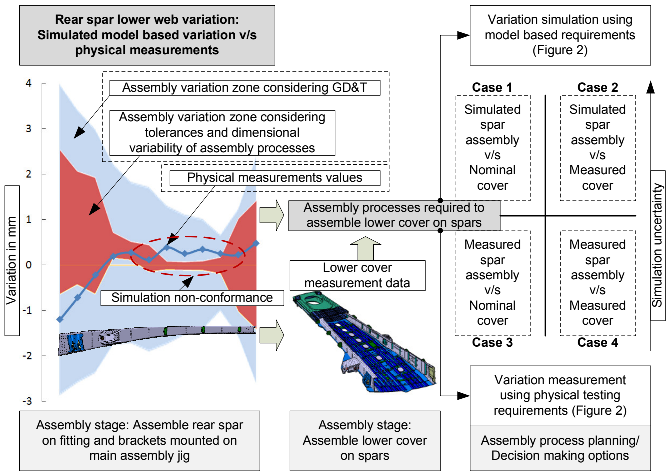

Figure 3. Model based simulation of assembly variability of rear spar lower web and consequential assembly process planning options

The simulation modelling results and the physical measurements from the previous assembly stage were utilised for planning the subsequent assembly stages, as shown in Figure 3. The subsequent assembly planning decisions were taken and iterated from case 1 to case 4, depending upon the accuracy of the simulation model to predict assembly variability and assembly build progress. For example, assembly planning decisions from case 1 can be taken at the initial design phase. This option initially involves major simulation uncertainty risk as no physical assembly build has began. On the contrary, case 4 can only be exercised after physical component manufacture has taken place; thus provide actual measurement data. However, as all the significant model based verification requirements were considered in the variability simulation model, the simulation uncertainty was lowered and early design verification was carried out via cases 2 and 3. In addition, this provides a mechanism to contextualise measurement processes and associated data with actual assembly build progress.

6. Conclusions

The methodology described in this paper provides a novel and coherent design verification environment for unifying and integrating the manufacturing and assembly processes for aero-structure assembly. The methodology is based on a novel, hybrid verification environment that is used to; (i) simulate component and assembly level variation due to designed tolerances, compliance and involved assembly processes; (ii) consider the effects of measurement assisted assembly technologies for making assembly planning decisions; and (iii) provide assembly planning options that are based upon the analysis of in-process, assembly measurement data. The hybrid design verification methodology has been applied in relation to a pilot wing box assembly of realistic design complexity with very promising results that demonstrated the overall process and validated the design and production benefits.

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