INTEGRATION AND INTERACTION OF VARIABLE-AXIAL FIBRE REINFORCED COMPOSITE COMPONENTS IN THE WHOLE ENGINE MODEL FOR FUTURE JET ENGINES

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Abstract

The paper presents the simulation methodology for a hybrid engine structure for future jet engine generations in the context of the whole engine model. In the complex system of a jet engine, the linkage of component simulation models to each other enables the analysis of the interactions and the improvement of the iterative development. The increasing requirements regarding the engine efficiency demand innovative design and manufacturing technologies, which lead to ever more complex models. Load path optimized variable-axial composite structures are to be considered on system model level to determine the structural behaviour under representative engine loads. To implement this approach, a suitable simulation strategy is developed. The following multiscale approach describes the modelling on component and sub-system level up to the integration into the whole engine model. The extraction of interface loads and retransfer on component level for further structural analysis is shown and validated. The elaborated virtual development method allows an effective but iterative design of all components of the hybrid intermediate case, taking the system conditions into account.

Key words: structural analysis, simulation method, virtual development, superelement

1 INTRODUCTION

Carbon fibre reinforced polymers (CFRP) with its high specific mechanical properties are predestined to improve the performance of conventional jet engines [1, 2]. The engine structure under consideration, as one of the most weight bearing components in the engine, offers a lot of weight saving potential due to a partially low material utilisation within the metallic part.

A hybrid metal-composite engine structure (HES) has been conceptualized by using metallic materials to introduce loads and handle complex three dimensional stress conditions. Composite materials on the other hand are inserted for load transfer, making use of load path optimised components.

During the detailed design process, innovative design [3] and manufacturing methods are introduced to meet the requirements towards the lightweight and structural integrity. The tailor fibre placement technology (TFP) has shown potential to increase the mechanical properties of a CFRP structure [4, 5] by creating variable-axial (VA) layups, where the fiber orientation can be varied within one ply. The work from Uhlig et al. and Dargel et al. [6, 7] indicates, that the virtual component models respecting the VA layup are of complex state.

Additionally, CFRP offer a lot of adjustable parameters that are to be analysed and optimized using representative flight load cases in order to provide suitable boundary conditions. Last but not least, the transition from a metallic integral design to a differential hybrid design leads to a more complex finite element modelling of the HES due to the additional metal-composite interfaces. The demands regarding the engineering design process based on [8-10] are increasing, while available time and resources are being reduced. To counteract this, effective tools and methods are required to improve the efficiency of the engineering design process on the virtual level [11]. Therefore, a simulation methodology within a complex structural environment was developed. This methodology was applied on the structural analysis of the HES.

The objective is to integrate a complex virtual VA component simulation model into its sub-system and system model and ensure a transition of the model between different software programs. The results of the complex system model are to be post-processed to analyse the influence of the component design parameters, taking the interaction of the whole engine structure into account.

2 THE HYBRID ENGINE STRUCTURE

The metallic reference structure of the component is shown in FIG 1. The inner cone (4), strut (7) and middle ring (6) are referred to as one part called torsion box. It contains several interfaces to the inner parts of the engine. The link 1 (1), link 2 (4) and link 3 (10) are the engine mount lugs, the interface to the aircraft fuselage. On the front side of the outer ring, the engine structure has an interface to the outlet guide vanes (OGV) (2) and on the backside to the bypass duct (8). Furthermore, the accessory gear box (AGB) (9) is mounted to the outer ring.

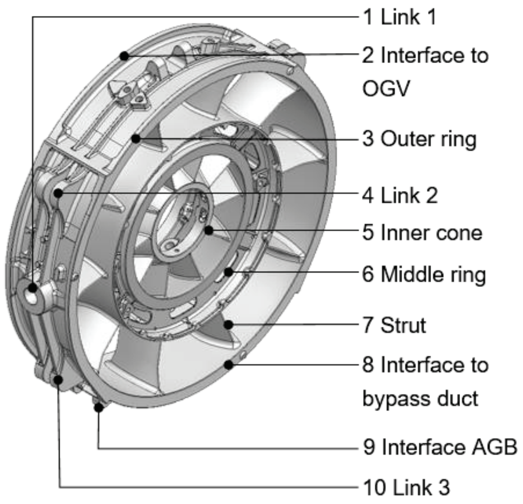

FIG 1. The basic structure and its associated parts

The structure locates the engine and transfers the generated thrust into the airframe. It has to provide a sufficient rigidity so that the minimal tip clearance between the fan blade and the fan case, which influences the efficiency of the whole engine, is guaranteed. Contrary to Rolls-Royce (RR) past jet engine architectures (cf. FIG 2, left), where aerodynamic functions have been handled by separate OGV, the engine structure of present generations of RR engines (cf. FIG 2, middle) unify both functions. The HES of future engine architectures consists of aerodynamic CFRP vanes in combination with structural metallic vanes (cf. FIG 2, right). The torsion box as well as the engine mount lugs are metallic, the outer ring is a CFRP structure. The components are connected through the following main three interfaces: torsion box to the vanes, the vanes to the outer ring and the outer ring to the engine mount lugs.

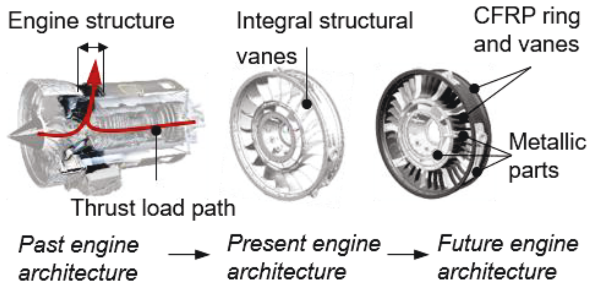

FIG 2. The engine structure within Rolls-Royce jet engine architectures

The HES CFRP components require a suitable structural design process to achieve the structural integrity for the considered load cases and fulfil the requirement towards weight saving and material usage. A VA-vane was developed [7] and is to be integrated on higher modelling scales (cf. FIG 3.) to perform a structural analysis. The complexity rises when moving from one scale to the one above due to the increasing number of parameters to be taken into account.

On the first scale, a suitable material is chosen and the material card is defined. Besides the mechanical properties and requirements, the manufacturing process drives the selection. The material cards are stored as xml-files.

The component scale describes design parameters of the HES components. For the CFRP components, the fiber laminate architecture - including the material, the fiber orientation, the single layer thickness and stacking sequence - are defined. The third scale is the HES itself, in which all components are assembled together. The last scale describes the whole engine and the integration of the HES into it.

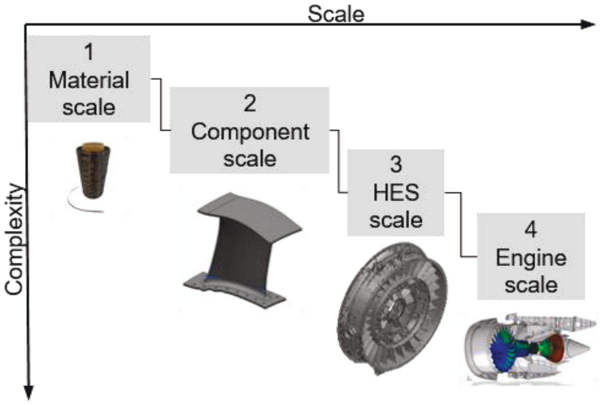

FIG 3. Multi-scales: from material to the engine

3 MODELLING APPROACH

3.1 Scale-based simulation method

First, four different and interconnected modelling scales, based on FIG 3, are defined: the component design modelling (1), the component simulation modelling (2), the sub-system modelling (3) and the system modelling scale (4). In order to ensure a smooth transition between the different software used, all data interfaces must be recorded beforehand (cf. FIG 4). The HES consists of several individual components, which are separately built up as CAD models (prt) in Siemens NX (NX). In this case, the design, aerodynamic and technology, such as joining and manufacturing technology, data inputs are provided by RR.

The models are further transferred to NX Simcenter to derive the finite element model (fem).

The sub-system assembly modelling is done in NX Simcenter as well and provides an assembly-fem-file (afem). The interface joining method is needed as an input. The WEM is a MSC Nastran (MSC) model, which consists only of coded dat text-files. Therefore the afem-file is exported from Simcenter as a dat-file and connected to specific nodes of the WEM using a script in Altair HyperMesh (HM). The output file from HM is Nastran bdf-file.

The system simulation, with the WEM as a data input, is run in MSC, which uses a different solver than NX. The solution output file can be set to the binary Nastran op2 result file or an ASCII format as e.g. the punch-file (pch). After solving, the interface loads are extracted from the result file, stored in an Excel sheet (xlsx) and retransferred on component simulation modelling scale. The extracted loads are used as input for the component simulation model (sim), which returns an op2/pch result file for the component post-processing.

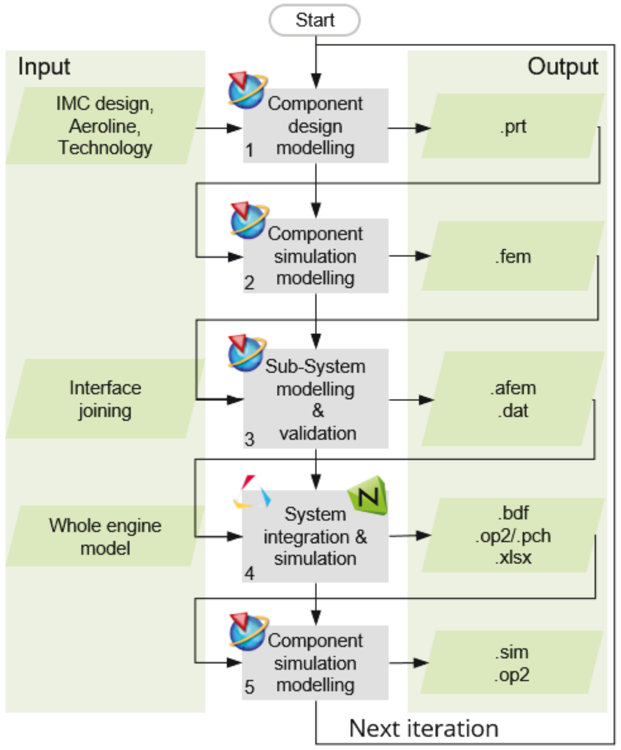

FIG 4. Simulation method with software interaction and data in- and output for the HES

The data compatibility between NX and MSC is to be ensured to allow the model transfer from component and sub-system scale to the system scale. The composite solid element property PCOMPS is not supported in MSC. During the TFP optimisation, PCOMPS property cards are created, which are not transferrable to the MSC solver.
For this reason, the developed methodology in this work is applied also on a CFRP multi-axial (MA) vane for validation purpose. Contrary to the VA-vane, the MA-vane is built up completely in Siemens NX using composite shell elements. The compatibility is ensured and model data conversion effort is reduced, but this approach can only depict MA laminate architectures.

3.2 Component modelling scale

3.2.1 Metallic parts

The HES consists of four parts - the torsion box with the metallic vanes, the CFRP vanes, the CFRP outer ring and the metallic engine mount lugs - that are to be modelled separately. To avoid that label conflicts occur in the sub-system or system model, a label range for each component is specified. Especially node, element, material and property labels are considered for traceability. A small buffer in case of remeshing parts at a later point is foreseen. The metallic torsion box and engine mount lugs are designed as 3D volume bodies. The fem-files are modelled with 3D ten-node quadratic tetrahedral elements (CTETRA(10)).

3.2.2 Composite structural multi-axial vane

The 3D-model of the CFRP vane consists of two platforms with an airfoil in between. From this model, a 2D mid-surface model is derived. The mid-surface model is used to build up the shell model of the MA-vane. Linear three-node tetrahedral CTRIA3 and four-node quadrilateral CQUAD4 2D elements are used in a zone based modelling approach with the PCOMPG property entry to depict the variable thickness of the airfoil. For the MA-model, the material orientation is defined through a tangent curve. The airfoil and the platforms are connected through an edge to surface stitch operation, which merges the face of the airfoil and the platform. This model is only used to validate the integration of the VA-vane into the WEM.

3.2.3 Variable-axial CRFP vane integration

The VA-vane is based on the same mid-surface model and mesh definition as the MA-vane. Contrary to the zone based approach, the thickness source is the mid-surface. The fibre path optimisation for the VA-vane is run with EDOstructure software from Complex Fiber Structures. The data process is shown in FIG 5. Based on the fem-file, the vane is exported as a dat-file from NX. This file is imported into Ansys Workbench to convert it into a cdb-file. The cdb-file is compatible to EDOstructure, where the optimisation is performed [7, 12]. Finally, the TFP vane is exported as a bdf-file, which can be reimported into Siemens NX.

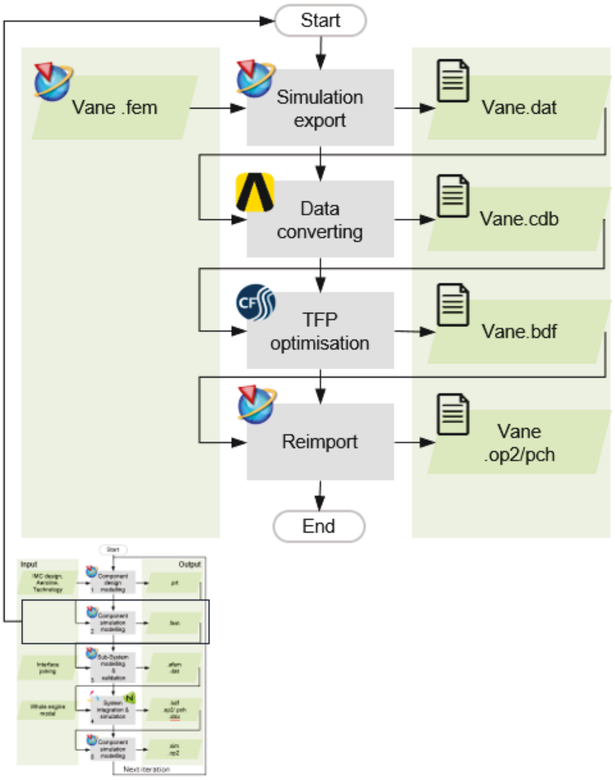

FIG 5. Data process for the TFP optimised vane

The TFP optimisation uses one element per layer to map the VA fibre orientation on each element. The three dimensional composite element type PCOMPS is created, which is not supported by the MSC solver. Therefore, the VA-vane is reduced as a superelement (SE), which can be included in the MSC solution as a direct matrix input

(DMIG). The data output format from the SE run can be set to an op2- or pch-file. The binary op2-file is used within NX, whereas the pch-file (ASCII) can be integrated as an external SE into MSC, allowing an embedding into the MSC solution (cf. FIG 6). The grid point bulk data entries are deleted from the pch-file, only stiffness and mass DMIGs remain.

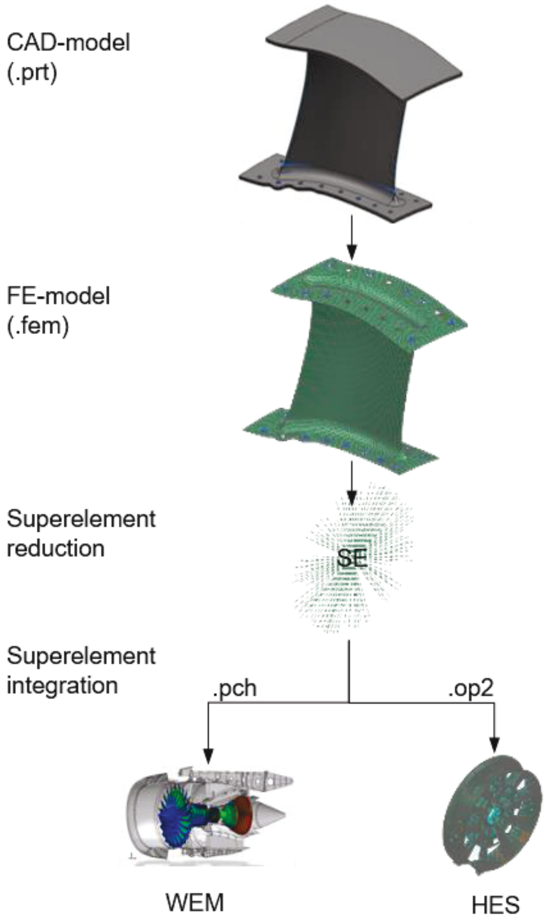

FIG 6. Vane superelement reduction and integration process for the variable-axial vane design

3.2.4 Composite outer ring

The CFRP outer ring is designed as a 2D shell model. The inner contour is chosen as a reference face, which leads to an extrusion of the laminate towards the outside. The ring surface is divided by the projection of contact surfaces of neighbouring parts in order to facilitate the mesh build-up.
The fem is modelled with linear quadrilateral four-node CQUAD4 2D elements. As for the CFRP MA-vane, the zone based modelling approach is chosen to apply different laminate properties to different zones via a PCOMPG entry. A colour code is used to highlight all contacting and functional surfaces as well as to validate the correct assignment of the mesh to its mesh collector. Due to the loss of the polygon geometry during the export of the simulation file for WEM integration, a detailed mesh collector definition is chosen. This later allows an adaption of one or more laminate parameters without reimporting the model into the CAE environment. The material orientation is defined by the vector method through the *Mesh Associated Data*. The shell normal vectors are checked and if necessary reversed, so that all normal vectors are pointing towards the outside.

3.2.5 Pre-process of assembly connection

The fem-files of the HES are connected through a bolted joint, which is modelled through a combination of a two-node 1D CBAR and a rigid beam element type 2 (RBE2). The CBAR represents the bolt whereas the RBE2 element are used to connect the end node of the CBAR to the washer or the bolt head area. Therefore, bore holes for the sub-system modelling are integrated into the interface surfaces already during the component design modelling (cf. FIG 7). To increase the adaptability, the contacting surfaces of the washer and bolt head around those holes are projected and divided directly within the part models instead of using the *Circular Imprint* command in NX Simcenter. A finer mesh in those areas is applied to decrease the appearance of potential singularities.
At the hole positions, the RBE2 spider elements with a master node in the middle are created. The master node is used to connect the parts on the sub-system modelling scale as well as to extract the loads on the system modelling scale. Because of this, the labels of the master nodes are carefully defined and chosen.

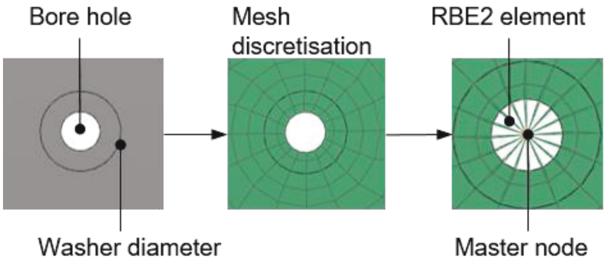

FIG 7. Modelling of the interface for the sub-system assembly

3.3 Sub-system modelling scale

On the sub-system modelling scale, all parts are loaded into one HES afem-file. The VA-vane is imported and replaced by the SE file through *Edit Representation*. After the import of all components, the assigned labels of each component are checked with the *Assembly Label Manager*. The connection of the parts is realised through the CBAR element (cf. FIG 8). The selection of the source and target node within the *Node to Node* connection defines the element x-axis, which has to be consistent for every CBAR.

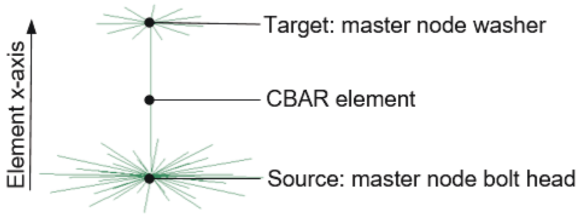

FIG 8. Modelling of the bolt joint

For each vane, a separate bar collector is created, which facilitates the post processing on the system-modelling scale. The results can be shown and exported explicitly for single bar collectors. The CBAR results are included in the solution by adding the force request to the structural output request. The fully assembled HES is shown in FIG 9.

FIG 9. Assembly structure of the HES

To validate HES model and the connection of the single components and their meshes, two solutions SOL 101 (static analysis) and SOL 103 (eigenvalue) are created (cf. FIG 10). It is a sub process of process step 3 (cf. FIG 4). For SOL 101, a unit load case is defined and an artificial constraint is applied. The simulation is run to check whether if any fatal errors or critical warnings occur. If so, the component simulation modelling is to be analysed towards the occurring error.
The SOL 103 is used to check if the components of the HES are properly connected. Since there are no constraints applied to the HES within this solution, it should have 6 rigid body modes, otherwise the HES is poorly assembled and needs to be reassessed.

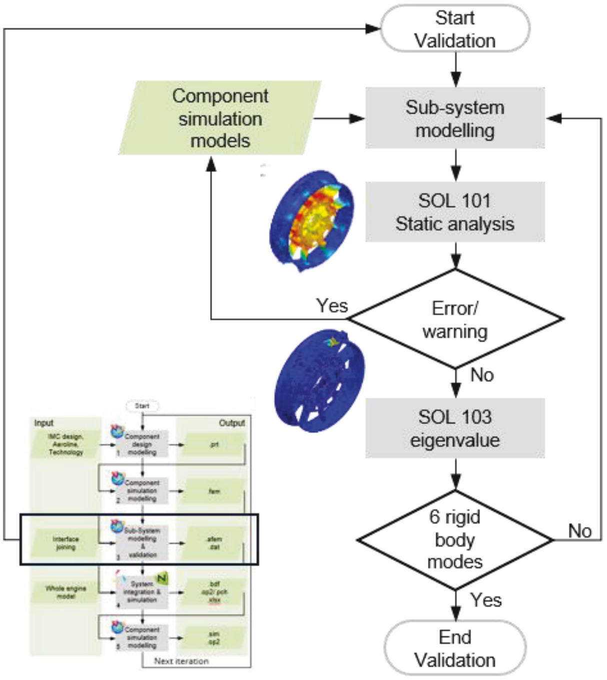

FIG 10. Assembly model validation process

Finally, the assembly model is exported as a dat-file. The SE bulk data entries are deleted from the file, only the grid point information to connect the SE to the residual structure remain.

3.4 System modelling scale and result retransfer

The structural analysis is carried out in the WEM. It is set up via several text-files containing the component meshes, connections, loads and boundary conditions. Those are included in one solution deck. The connection of the HES to its adjacent components is done in HM. As a first step, the dat-file from sub-system modelling is imported in HM to prepare the HES for the connection process. Subsequently, the HES is exported as a bdf-file and the connection process is performed. After that, the connected HES is again exported as a bdf-file and, together with the SE-file, integrated in the WEM solution deck via include commands. Through the structural output request, the data type, data output medium and quantity are set. The selected data types for the load extraction are displacement and force. The default data output medium is a binary op2-file. The data type output quantity can also be controlled. Since only the interface loads to the CFRP vane are of interest, it is set to a group reference which contains the interface element and node information. This means exemplarily for the force output, that only the forces from referenced CBAR elements are written to the result file. Thereby, the result file size is significantly reduced.
Once the WEM is solved, the op2 result file is reimported into Siemens NX for post-processing. The displacements at the interface nodes are exported to an Excel sheet.
A sim-file of the VA-vane fem is created with SOL 101 static analysis and the extracted displacements are applied as an enforced motion load. The referenced coordinate system has to be consistent with the one from the imported op2 result file. The node label and position are to be checked again to ensure the correct retransfer of the results to the related nodes. Once pre-processing is finished, the sim-file is solved and can be post-processed.

3.5 Validation of the interface load extraction

The reduced SE of the VA-vane cannot be post-processed in the result file from the WEM. For this reason, a comparison of the structural behaviour of the system model and the component model with the enforced motion load applied is not possible. In order to validate the developed methodology, the unreduced model of the MA-vane has to be integrated as a dat-file in the WEM. This model is also reduced as a SE for result comparison. The WEM is run twice, first with the unreduced MA-vane as a dat-file and second with the reduced SE of the MA-vane.
The results of the MA-vane in the WEM (cf. FIG 11, left) and the component model with the extracted displacement from the second WEM run (cf. FIG 11, right) for the displacement magnitude plot show a similar deformation for both airfoils. The approach of load extraction from system scale and retransfer on component scale is thus validated.

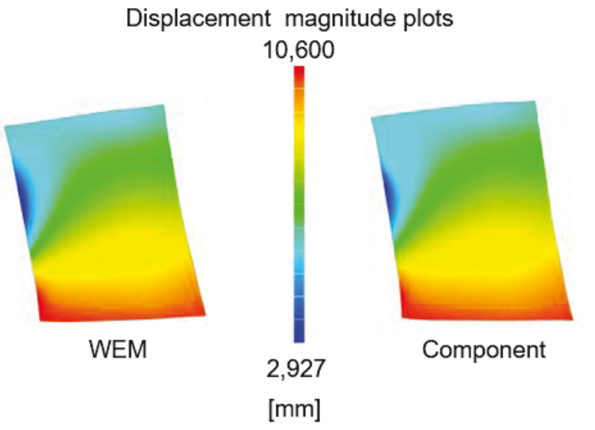

FIG 11. Displacement plot for one representative load case in WEM (left) and with applied enforced motion load on the component (right) for the MA-vane

4 RESULTS

The virtual development method (VDM) for the HES is shown in FIG 12, taking all modelling scales as well as the retransfer of the component results into account. Seven main phases were identified: the component scale, the sub-system assembly, the sub-system scale, the system integration, the system scale, the system post-processing, the load extraction and retransfer and the component simulation. Those phases are to be iteratively considered, until the design adaption deliver optimal system responses.

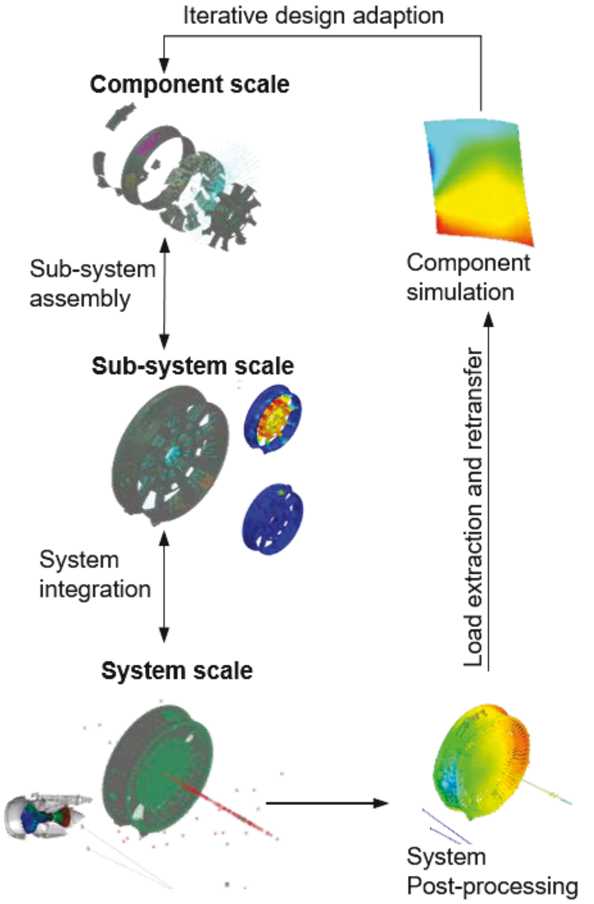

FIG 12. Virtual development method for the HES in the context of the whole engine

5 CONCLUSION AND OUTLOOK

This paper presented the development of a methodical simulation approach for the integration of a complex VA structure in the WEM for future jet engine generations. The VDM enables the structural analysis of complex component models taking representative engine load cases into account.

The defined multi-scales allow a cross-scale holistic view of the component structural analysis. A systematic approach to model a component in the context of the sub-system and system was shown. The transition between different software tools was highlighted and a method to integrate the TFP VA-vane model into the sub-system and system model was demonstrated. The assembly of all parts with representative joining elements as well as a pre-validation strategy was implemented. The displacements were extracted during system post-processing and retransferred on the component model. Based on a MA-vane model, a comparison of the system and component results was carried out to validate the procedure.

This method is adaptable to other complex systems and can be scaled to larger and more complex jet engine models. Besides the structural analysis and validation of the components, the extracted loads can be used as a load boundary input for optimisation algorithms. The TFP optimisation can be set up again with an updated load boundary condition. Exemplary for the metallic parts of the HES, a topology optimisation can be set up. In addition, the load extraction at the interface nodes allows the sizing of the joining elements. Their parameters - as type, material, diameter, number et cetera - can be examined.

Furthermore, a parameter interaction and correlation analysis can be carried out. The influence of e.g. the material parameter can be investigated on the system scale and its response can be plotted on component scale.

For physical testing, the boundary conditions can be derived for virtual-physical test campaigns.

Based on the developed data process flows, the digital linkage between the data is to be increased. Especially the retransfer of the loads is of interest, so that the VDM can be carried out partly automated. The data transfer must be further analysed to enable automated data in- and output between the software interfaces.

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