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Demonstrating an approach for multidisciplinary set-based design within an aerospace research project - DEFAINE

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Abstract

There is a need for more sustainable aviation solutions, and the aerospace industry is increasing its efforts towards alternative and more sustainable technologies such as battery powered electrical engines and different hydrogen variants. This paper describes an approach for multidisciplinary set based design within a European aerospace research project, DEFAINE. The project is a collaboration between aerospace manufacturing industry, software providers and academia. The result presented is based on the first step of development in one of five use cases in the project. A Design space exploration process for an aircraft engine component is described and evaluated against KPI:s. There has been development in the automation of the different steps to reduce the time needed to update and run the process. The project is expected to provide more innovative and cost efficient solutions as a larger design space is covered within a shorter time span compared to conventional/traditional PD projects. The approach is demonstrated by an industrial use case within one of the participating companies and includes a scenario where requirements are represented as a set of ranges instead of discrete numbers. These set of ranges represents a requirement space where every unique instance of requirement can have a number of possible solutions as well as an "optimal" solution. The paper describes the use case together with metrics for evaluation against key performance indicators (KPI:s). The evaluation criteria is defined based on industrial need identified in the research project. A generative model can automatically create aero CAD geometries based on aero definition generated by an in-house aero design tool. This increases the design space dimensionality and will enable broader multidisciplinary design space exploration studies. The work presented is based on current results from the development in the DEFAINE project. Further work will focus on the complete DSE process where the ambition is to demonstrate how DSE studies can provide data for better decision support. Here, different AI algorithms will be tested to support prediction modelling together with interactive data visualisation tools, such as parallel diagrams

Keywords: MDO, KBE

1. Introduction

There is a public demand for more sustainable aviation solutions, and the aerospace industry is increasing the efforts towards alternative and more sustainable propulsion technologies such as battery powered electrical engines and different hydrogen variants. For aerospace engineers, this provide a challenge as new type of technical solution needs to be designed and assessed.

This paper describes an approach for multidisciplinary set based design within an aerospace research project, DEFAINE [1]. The project is a collaboration between the aerospace manufacturing industry, software providers and academia.

The aim of the approach is to;

- Reduce the number of iterations conducted in a PD project.
- Increase the number of design variants studied

This is expected to provide more innovative and cost efficient solutions as a larger design space is

covered within a shorter time span compared to conventional/traditional PD projects.

The approach is demonstrated by an industrial use case within one of the participating companies and includes a scenario where requirements are represented as a set of ranges instead of discrete numbers. These set of ranges represents a requirement space where every unique instance of requirement can have a number of possible solutions as well as an “optimal” solution.

The paper describes the use case together with metrics for evaluation against key performance indicators (KPI:s). The evaluation criteria is defined based on industrial need identified in the research project.

The result presented is based on the first step of development in one of five use cases in the DEFAINE project. Here, a Design Space Exploration process for a FOGV unit is described and evaluated against KPI:s. There has been development in the automation of the different steps to drastically reduce the time needed to update and run the process.

European players are forced to explore new product development approaches that can drastically reduce lead-time. The DEFAINE project is expected to accelerate the entry into service of novel solutions and remain competitive. DEFAINE will deliver an advanced Design Exploration Framework able to reduce recurring cost in design of aircraft by 10% and reduce the lead-time for design updates by 50%.

Multidisciplinary design optimization is here defined as the field of engineering that uses optimization methods to solve design problems incorporating a number of engineering disciplines. MDO allows designers to incorporate relevant disciplines simultaneously. The optimum of the simultaneous problem is superior to the design found by optimizing each discipline sequentially, since it can exploit the interactions between the disciplines. However, including all disciplines simultaneously significantly increases the complexity of the problem. This research follows advancements in multidisciplinary design automation in the field of mechanical engineering and aerodynamics to optimize product geometry [2] [3] [4] [5]. The automation capabilities within Computer-Aided Design (CAD) software enables design engineers to automatically generate large number of different design variants through the creation of master CAD models [6]. At the same time, there are significant achievements provided by software providers in automated analysis to evaluate these models, e.g. AnsysWorkbench™, Hyperworks™, Siemens Simcenter 3D™. In addition, the incorporation of statistical analysis and Design of Experiments techniques for design space exploration has enabled building prediction models for product performance. Prediction models are based on conducted simulations that allow estimate the functional performance of parametric combinations (design variants) within the design space that have not been simulated [7] [8].

2. Structural Outlet Guide Vane

The use case describes a process for a Design Space Exploration (DSE) study of a Structural Outlet Guide Vane (SOGV) for in an electric aircraft engine, see Figure 1. GKN Aerospace, in collaboration with KTH Royal Institute of Technology, is developing fan technology for regional electric aircraft as part of the EleFanT (Electric Fan Thruster) project. The SOGV is component that directs the airflow and provide support for the engine bearing housing that canters the engine shaft in a turbofan engine. The SOGV outer ring is in turn attached to the aircraft. The component integrates several functional requirements in one component.



Figure 1 - Visualization of the EleFanT engine

Disciplines included in this use case are aerodynamic performance, mechanical function and producibility as illustrated in Figure 2. The objective with the Design Space Exploration study is to find feasible and robust solutions with minimum weight and cost that fulfils the requirements.

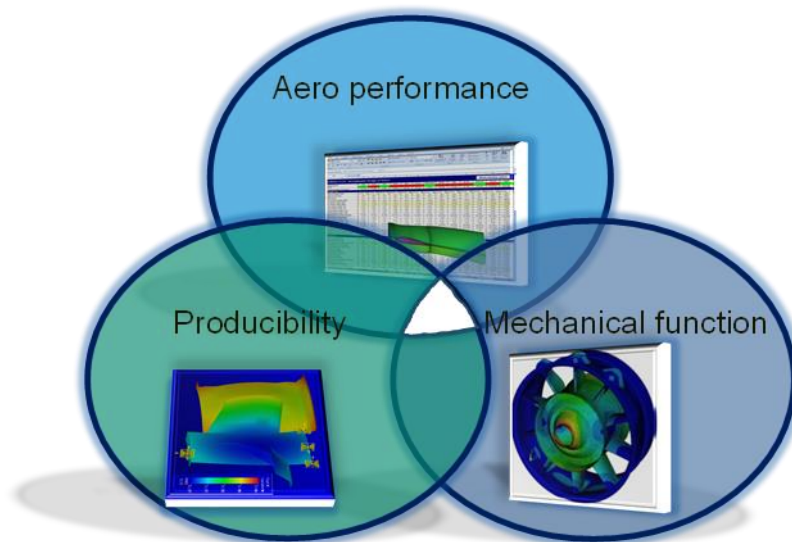


Figure 2 - Multi-disciplinary design, finding the right balance.

Instead of designing for a single point in the range of requirements, a set of solutions are designed that satisfies the set of requirements. This results in several optimized solutions that corresponds to the range of requirements. The approach requires a large number of optimization tasks and analysis to provide spectra of solutions for the design space. Figure 3 - illustrating the Set-Based funnel and sharing of data between different system levels.

Set based process - System level <-> sub system level

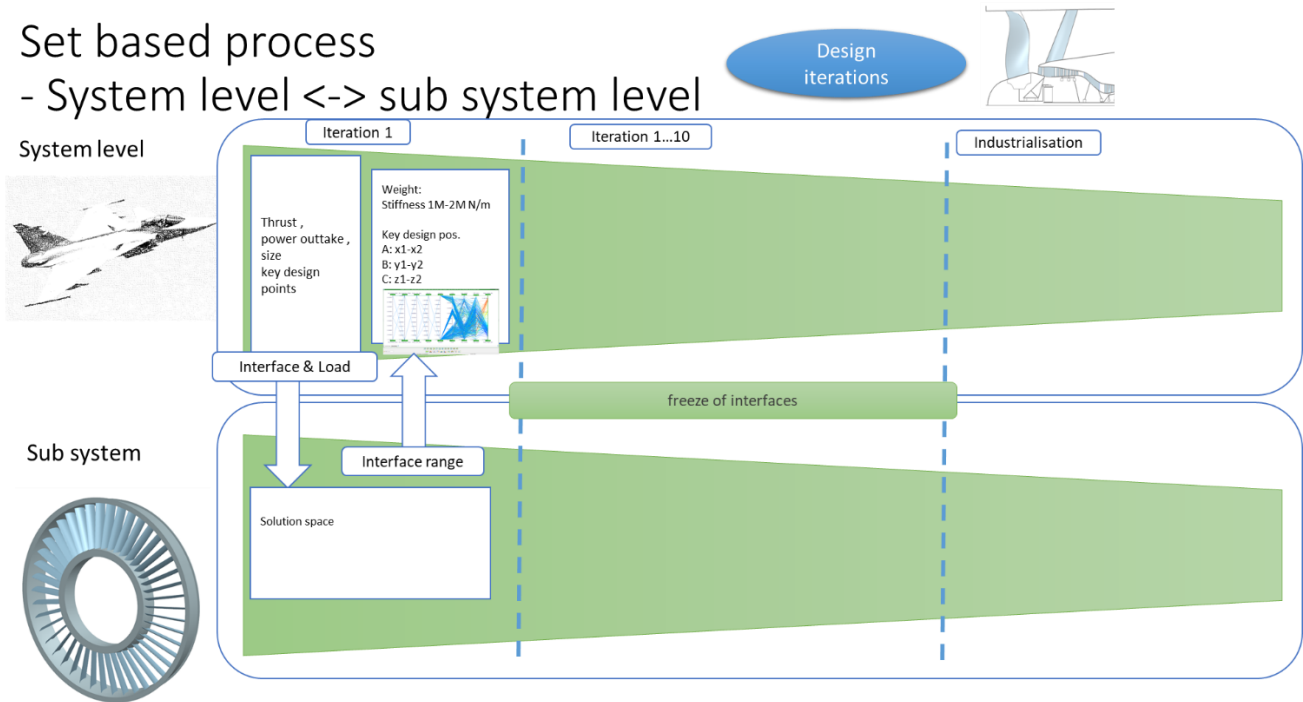


Figure 3 - illustrating the Set-Based funnel and sharing of data between different system levels.

The set based approach provide a better understanding of how the different requirement parameters such as interface position and mechanical loads effect the component and enables a more “robust” design concept, avoiding to choose a single concept that might not meet changes in the requirement later in the product development process. By providing a response surface model instead of a single design, the engine architect have a better understanding of how changes in the requirements effect the mechanical and aero dynamical characteristics of the component and can avoid updates of interfaces that are known to be unfeasible from a component design perspective.

3. State of practice process description

GKN Aerospace Engine is developing an engineering framework environment for Design Space Exploration and Optimisation called Engineering WorkBench, See Figure 4 - GKN DSE framework overview. The framework includes GKN standard tools for design and analysis of concepts. This is a heterogeneous framework consisting of tools from several different software vendors. The main requirements for each module/tool in this framework are that it needs to be able to run automatically and exchange data in predefined GKN standard formats.

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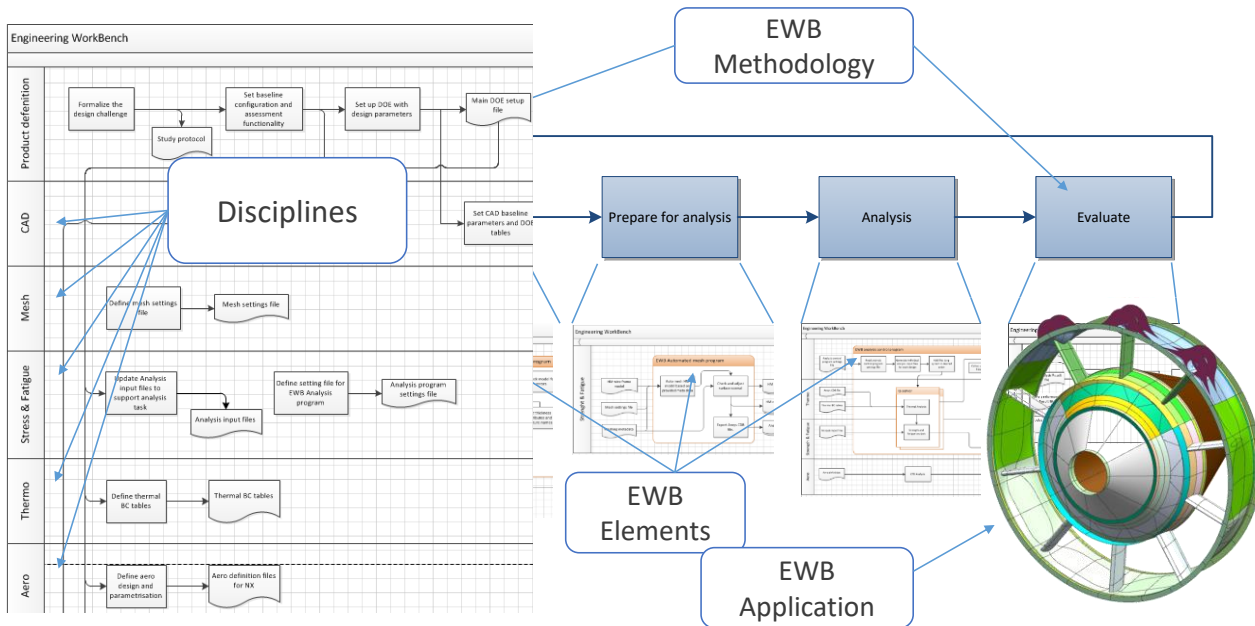


Figure 4 - GKN DSE framework overview.

The framework is built around a generic process for evaluating designs; in short, this translates into the following steps:

1. Prepare design input data needed to setup and run a design study.
2. Generate 3D solid models with meta data, context model needed for the analysis.
3. Prepare for analysis. Generate / update mesh.
4. Run solver.
5. Visualize results. Create trade curves, pareto front diagrams, parallel diagrams, etc.

The current baseline process for conducting a DSE on a SOGV is semi-automatic and several steps are executed manually, the process is illustrated in Figure 5 - describing the generic DSE process.

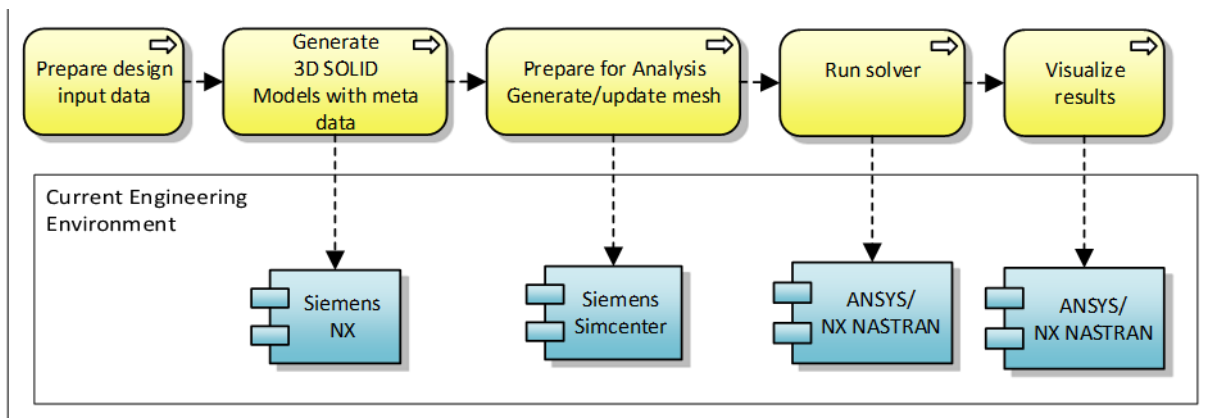


Figure 5 - describing the generic DSE process.

The DEFAINE project develop technology to automate steps that are currently manually managed by an engineer. This enable a DSE that provides the engineer with an improved understanding of how the variation in requirement's effect the solution space.

4. Development and benchmark results

This chapter describes how the use case perform in relation to the different criteria's. The evaluation criteria are defined based on industrial input and where GKN Aerospace has identified a need for improvement. There are several more KPI:s defined in the DEFAINE project that are not included here, as this publication only covers the current progress in one of the industrial use-cases.

The work so far has improved the following KPI:s that are targeted in the project.

- Lead-time for design update
- Design space coverage / Dimensionality

4.1 Lead-time for design update

This evaluation criteria relate to run time when executing included tools for generating designs and analyse. The KPI is primarily improved by automation of engineering tasks.

4.1.1 Benchmark use case

The benchmark use case includes three manual steps, 1. Update/generate context models (CAD), 10 CAD models are created and stored at a network repository. 2. The FEM mesh is updated. 3. Performing stiffness analysis for two load cases, calculate weight and Aero area blockage.

Create context models

Update of CAD models including the following parameters:

- Number of vanes
- Vane thickness

When updating the Number of vanes, section splines are imported and a surface is swept through the section splines to form a vane. The Vane is then copied around in a circular pattern.

Manually updating the CAD models normally takes 5 min per model, resulting in a benchmark time of 50 minutes for 10 models.

Prepare for analysis

Meshing parameters used in this use case is:

Volume Mesh, Average Element Size 6 mm

Aspect Ratio 10

Internal Grading 1.3

Tet Collapse Min Value 0.12

Jacobian-Ansys 0.1

The mesh used for the geometry in this use case takes 30 min per model, resulting in 5 hours total for the mesh generation.

Analyse

The analysis included in this use case includes Stiffness analysis, max geometric area blockage and weight.

Two different stiffness values are calculated, one for vertical stiffness and one for Over Turning Moment (OTM). Both analyses are given take-off temperature condition and the thermal expansion is turned off.

For the vertical stiffness the model is locked at the forward flange and a force is applied at the center mass node, see Figure 6 - SOGV boundary condition.. The mass node is connected to the bearing with constraint equations. The stiffness is measured as: $\text{stiffness}_{ux} = \text{unit_load}/ux(\text{post_node})$, where post node is where the load is applied.

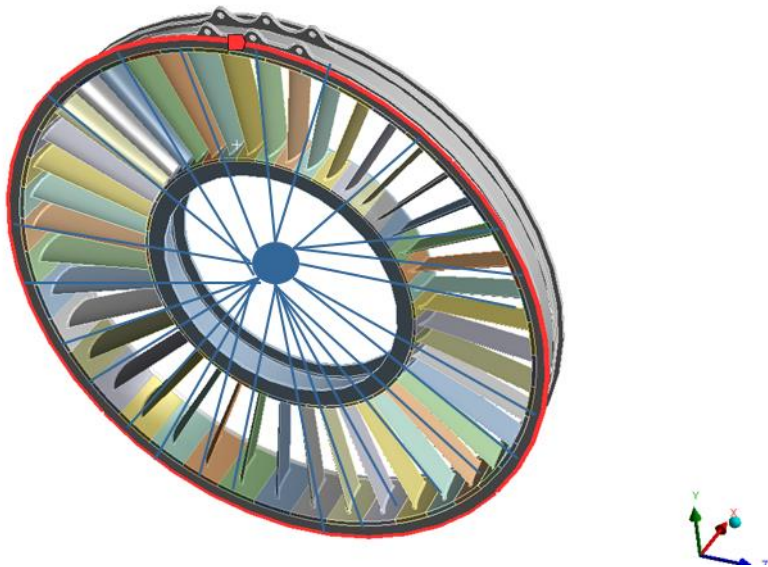


Figure 6 - SOGV boundary condition.

The time for completing the analysis in this use case takes 8 min per model giving a benchmark time 1h and 20min.

Stiffness OTM is an analysis that measures the overturning moment stiffness. The model is locked same as previous and a moment is applied at the center mass node around horizontal axis. The mass node is connected to the bearing with the constraint equations. The moment applied is 10000 Nm. The stiffness is measured as: $\text{stiffness_roty} = \text{unit_load}/\text{roty}(\text{post_node})$, where post_node is where the load is applied. The time for completing the analysis in this use case is equal to previous loadcase.

The max geometric area blockage is calculated for the CAD model to extract a single number that can be used as a qualitatively representation of aerodynamic performance. This is almost instant and the benchmark time is set to 1 second. The weight is calculated in the CAD model and the result is written in a text file. The manual process for this takes approx. 2 minutes per model.

4.1.2 Achievements in DEFAINE

A generative model has been developed that automatically generates geometries based on both numerical input parameters as well as aero surfaces provided as spline definitions in textfiles. The geometry is tagged with meta data to support the automated mesh process with information of material as well as load points. The development of these models has reduced the generation of CAD geometry to 1 min per model, giving 10min for 10 models.

An application using NX open in Simcenter 3D to automatically apply loads and generate a mesh on the geometry has reduced the time to prepare for analysis to 5 min per model giving 50 min for 10 meshed models.

We have included more advanced CFD design and analysis, however this is more time consuming and does not reduce the time, hence not comparable with the simplified aero blockage calculation in terms of time.

A script has been created that automatically take out the weight and export the results for all included parts to a text file. This reduces the time for calculating the weight and write the results in a file to approx. 5 sec.

No improvements has been made for the stiffness analysis task.

4.2 Design space coverage / Dimensionality

This is a measure for the completeness of design space coverage. The metric is here set to;

- The number of parametric alternatives that can be studied.
- Types of analysis/assessment.

4.2.1 Benchmark use case

Number of included parameters are:

- Number of vanes
- Vane thickness

Types of analysis/assessment

- Stiffness analysis
- Max geometric aero blockage
- Weight

4.2.2 Achievements in DEFAINE

A KBE application has been integrated in the model that automatically generates geometries based on both numerical input parameters as well as aero surfaces provided as spline definitions generated by an in-house aero design tool with key aero parameters.

Several more geometrical parameters are added that controls the rib stiffness, mounting dimension and together with hub and shroud thickness.

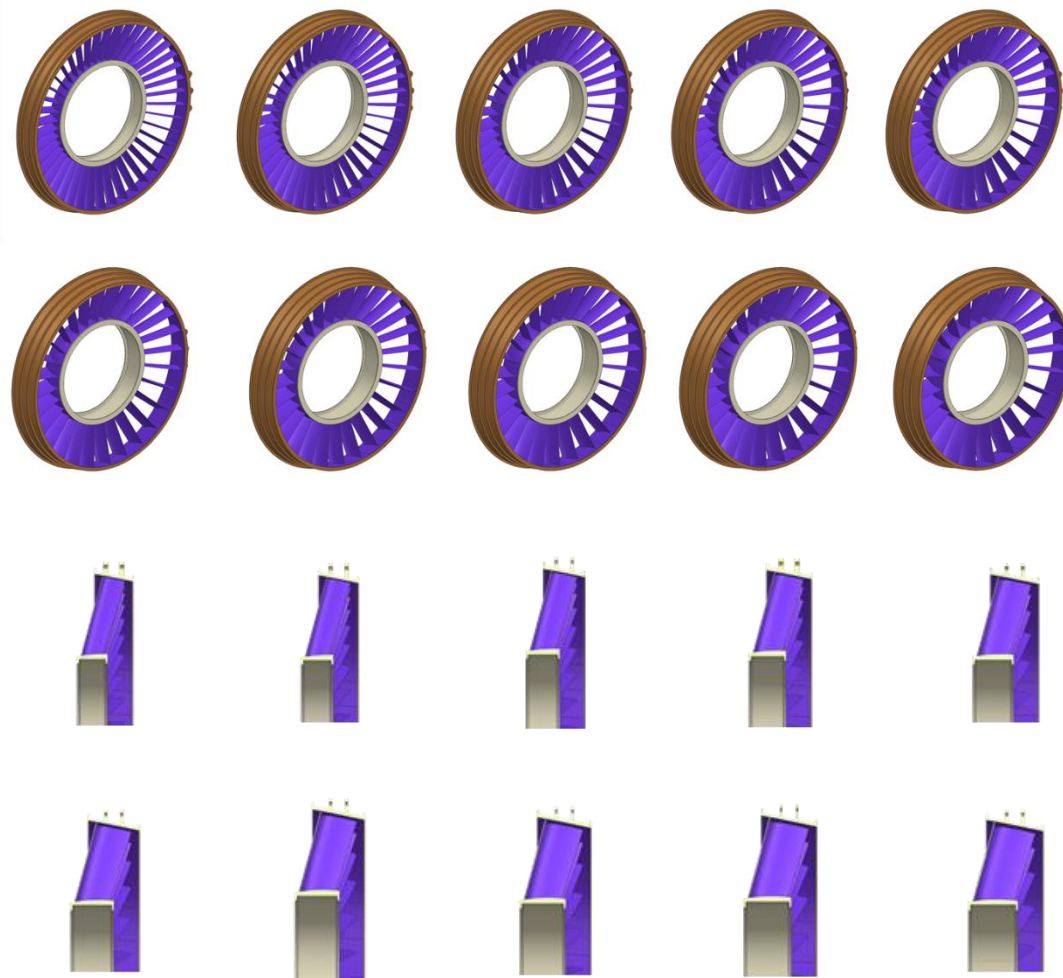


Figure 7 – Illustrating parametric variation of the SOGV.

The aerodynamic geometry is designed and assessed using G3DFlow, an in-house CFD code developed by Chalmers University and GKN Aerospace. G3DFlow is a density-based, finite-volume flow solver using a three-stage Runge-Kutta time marching method. The turbulence model used is the realizable k-ε turbulence model with the Kato-Launder limiter. The computational domain, illustrated in Figure 8, ends the same axial location downstream of the outlet guide vane for all geometries analysed. Both the fan geometry upstream of the outlet guide vane as well as the outlet guide vane itself are included as part of the analysis. A single blade is modelled in each blade row, using a periodic boundary condition to account for the full annulus. The computational mesh consist of approximately 500 000 grid elements in each blade row. The performance of the different blade geometries was evaluated at the same operating point, defined by a throttle area [9].

The fan geometry remain fixed and the blade count of the SOGV is varied from 44 down to 24 while maintaining constant solidity (solidity=chord/pitch). A lower blade count thus implies a longer chord, illustrated in Figure 8.

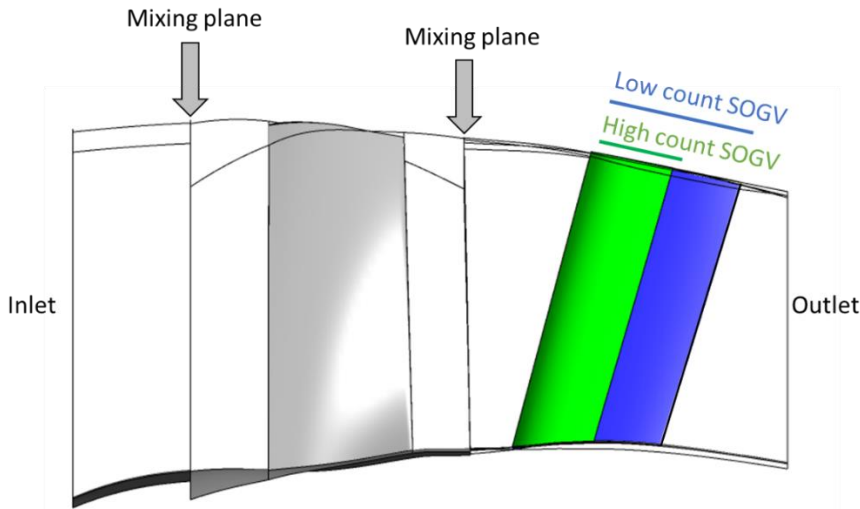


Figure 8 - Computational domain. High count (44) SOGV shown in green. Low count (24) SOGV shown in blue.

The CFD result files are post-processed automatically, and the impact of the SOGV blade count on the loss coefficient relative to the baseline blade is shown in Figure 9a. The loss coefficient, ω , is defined in Eq. 1 where P denotes pressure and the subscript 0 denotes total condition. Station 1 and 2 denotes the inlet and outlet of the SOGV part of the computational domain.

$$\omega = \frac{\bar{P}_{01} - \bar{P}_{02}}{\bar{P}_{01} - \bar{P}_1} \quad \text{Eq. (1)}$$

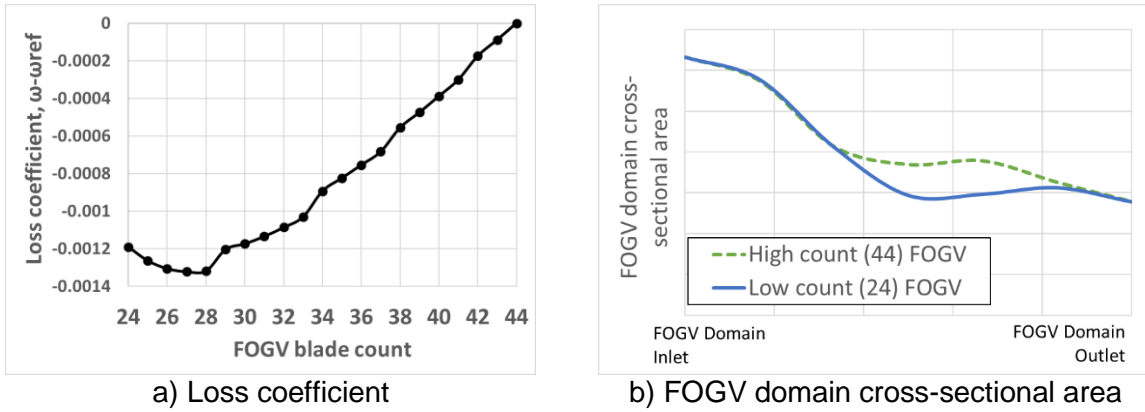


Figure 9 - Results from CFD analysis and cross-sectional area evaluation

The reason for a reduction in loss coefficient with a reduction in blade count, albeit small, is not immediately clear. If the hub and shroud had been horizontal, the surface area of the blade and end-walls would be expected remained the same for all blade counts. However, the end-walls are not horizontal, they are contoured to produce a flow area reduction. Consequently, as the blade count is reduced and the blade chord is made longer, the total surface area of the blades and end-walls is reduced. Considering the same velocity of the flow, a reduction in surface area would result in a reduction of friction losses. However, the cross-sectional area in the SOGV domain varies as the blade count is changed, illustrated in Figure 9b. A contraction of the area increase the velocity of the flow, which acts to increase friction losses. For a lower blade count, the flow area reduction at the location of the blades is greater and over a larger part of the duct, leading to a higher flow velocity for a longer section of the domain. Further aspects that can influence loss include Reynolds number effects and secondary loss variations [10].

The integration of the in-house CFD code has increased the design space dimensionality and will enable broader multidisciplinary design space exploration studies.

5. Conclusion and further work

The result is based on the first step of development in the DEFAINE project. A Design Space Exploration process for a SOGV unit is described and evaluated against KPI:s. In this first step the development has aimed to automate the different steps exploring different techniques such as KBE technology to reduce the time needed to update and run the process.

The developed generative models has reduced the generation of CAD geometry from 50 min to 10min for 10 models and reduced the time to mesh of these models also from 1 hours to 50min. However, the main reduction in this process lead-time is gained by excluding the repetitive and tedious work done by the engineer. In practice, the availability of an engineer that can prioritize this work is often limited, making the real lead-time far longer.

Several more geometrical parameters are added that controls the rib stiffness, mounting dimension and together with hub and shroud thickness.

In addition, the developed generative model can automatically create free-form aero CAD geometries based on aero definition generated by an in-house aero design tool. This increases the design space dimensionality and will enable broader multidisciplinary design space exploration studies.

There is a need to include more analysis for aero performance metrics, stress analysis as well as an automated produceability assessment.

The work presented is based on current results from the development in the DEFAINE project. Further work will focus on the complete DSE process where the ambition is to demonstrate how DSE studies can provide data for better decision support. Here, different AI algorithms will be tested to support prediction modelling together with interactive data visualisation tools, such as parallel diagrams.

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