

A master-model approach to whole jet engine analysis and design optimization

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1. Abstract

Novel jet engine concepts and architectures are being explored to reduce mass, fuel consumption, development cost and environmental impact while increasing performance. Although the engine systems development process of the next generation aero engines takes place at the original equipment manufacturer level, component manufacturers need to optimize their components using an integrated engine system design approach. Therefore, they need the capability to model and simulate whole engine behavior. While modeling and simulation are traditional strengths of the aerospace industry, model integration of the whole engine system and its components, as well as between separate disciplines, is still a relatively weak link. This paper presents a master-model approach that facilitates integrated analysis used in design optimization. The master-model approach promotes the existence of a single governing version of the product definition, including associated versions of loads, materials, interfaces, constraints etc. A simple yet illustrative industry application is presented where dynamics and displacement analysis are performed using the master model and a parameter study is performed to find an optimal design. The presented scenario investigates the impact of changing the bearing position of the turbine rear frame of a turbo-fan engine considering the load case of a “fan blade off” event.

2. Keywords: Whole engine models, integrated analysis and design optimization, knowledge-based engineering

3. Introduction

Reducing mass, fuel consumption and development cost while increasing performance are the traditional drivers of aircraft engine design. Significantly reduced environmental impact is an additional, and increasingly important, design objective (see, e.g., [1]). Novel engine concepts and architectures are being explored and investigated to meet these challenges.

As component manufacturers supply jet engine parts to original equipment manufacturers (OEMs), it is desirable to design components using a systems (whole jet engine) approach in order to optimize component design for system-level performance. There are, however, several issues that hinder this approach in current practice. Continuously updated information (such as component boundary conditions) is not readily available from the OEM since the engine system architecture undergoes configuration changes. Component manufacturers have a need for models that effectively integrate the product definition with the analysis activities during early product development activities. Aircraft design is traditionally strong in modeling and simulation but model integration and minimization of redundant information is still relatively weak due to the advanced, but domain-specific, methods used. These multi-domain design strategies results in time-consuming (and sometimes unnecessary) definition and analysis tasks. This is particularly true where organizational boundaries have to be crossed. Moreover, component manufacturers are often forced to work with engine system and component simulation models that have different levels of fidelity and are not integrated. There is therefore a need to strengthen the capability to model and understand the engine component behavior in the entire jet engine system context. The properties of engine components must be optimized to satisfy targets that are set on engine system level, rather than on properties derived at component-system boundaries.

The objective of the work presented in this paper is the development of a useful model for structural whole jet engine analysis and design, including effective information management and optimization. Earlier work on aircraft analysis and design models focuses on computer-aided design (CAD) and analysis integration (see, e.g., [2]) and knowledge-based engineering [3; 4]. These works offer opportunities for further investigations in the context of component manufacturer design for system performance. In particular, this paper presents a master-model (MM) approach that facilitates integrated design and analysis. The master-model approach aims at minimizing information being stored at multiple places; instead, one master product representation provides all the information necessary for analysis and design. One analysis activity at a time can access information; results guide the change of the master model. Another analysis activity can then access updated information, and its results guide further updates of the master model. In this manner, product representation is updated during the optimization process, which invokes multiple analyses.

A simple yet illustrative industry application is presented where dynamics and displacement analysis are performed using the master model. This integrated analysis and design optimization framework is then used to examine what-if scenarios rapidly. The presented scenario investigates the impact of changing the bearing position of the turbine rear frame of a turbo-fan engine. The considered load case is a rotating unbalanced mass due to a “fan blade off” event (losing a fan blade during engine operation). The design objective is defined by minimizing both the displacement and the mass.

4. Knowledge-based engineering methods

Knowledge-based engineering (KBE) is a fundamental concept of the master-model approach proposed in this paper. Stokes, [5], defines KBE as “*the use of advanced software techniques to capture and re-use product and process knowledge in an integrated way*”. The ambition to automate engineering design chains are not new, and has been the approach for experienced engineers for a long time. Along with the development of computer aided modeling and simulation tools several approaches can be listed [6-8]. KBE emerged from the launch of the CAD software ICAD [9] and increased in popularity during the 90’s and 00’s when useful mechanical engineering applications were reported, see e.g., [10-13]. KBE aims at making engineering design more effective by i) automating routine and time demanding tasks through formalizing captured explicit knowledge into rules and ii) showing design change implications on downstream activities, e.g. cost, manufacturability, maintainability, etc. KBE commercial software is often coupled with automated mechanical CAD; KBE-modules coupled to CAD-packages include Siemens PLM NX, [14], and Dassault System Catia, [15]. KBE applications for automatic finite element pre- and post-processing has also been reported [16; 17].

Kessler [4] presents a generic framework for multidisciplinary optimization (MDO) which uses an Integrated Design Model to integrate numerous analyses. The framework is exemplified for wing design and analysis where geometry is generated through a knowledge-based engineering module and optimized for structural analysis. Then an aerodynamic analysis takes place. This example has a text file as integrated design model and has manual preprocessing, e.g. meshing and loading, and the design and analyses are done in one main iteration loop. This work couples to the intent of the proposed MM approach to integrate design and analysis and enable optimization. One limitation of the approach presented in [4] is the lack of changing the design for each analysis rather than going through the whole loop.

A strategy for aircraft design which is automated and implemented in software is reported by Hwang et al., [2]. The software utilizes a gradient-based optimization technique, response surface modeling, and Carpet plots, to find an optimal design. The proposed MM approach deals with information management strategies and CAD-based product definitions. In [2] the information is handled in several databases and a commercial CAD software is programmed through the API (Application Programming Interface) and a GUI has been created with C++ to aid inexperienced designers. Aerodynamics, mass, stability and control, propulsion and performance analysis are included. Geometry generation is semi automatic and designers can (manually) search for existing aircraft configuration solutions that are relevant to their current task. One limitation of the approach presented in [2] are the manual search for existing configuration solutions.

La Rocca and van Tooren [3] presents a design system that enables MDO supported by KBE. The core unit of the system consists of a multi-model generator (MMG) that based on a high level primitives concept can generate numerous aircraft configurations. The MMG can also extract data and information from the product definition to specific analysis. Design (product definition) changes are propagated in an automated fashion to all analysis models. A toolbox checks the analysis convergence and compares results with the design specification. If failing to satisfy the specification the toolbox can trigger new design iterations. The ability to extract data and information from the product definition to use for analyses is also targeted in the proposed MM approach.

A common limitation of existing approaches is that they are either stand-alone integrated solutions or that they can support only domain-specific applications. While thermal – structural analysis integration has been discussed and studied, few applications report multi-disciplinary optimization.

5. Master-model approach

Within CAD, the master-model approach is established to create one definition that is used for CAD, CAM and CAE and is automatically updated for all applications given a design change (see, e.g. [18]). The aim of the master-model (MM) approach presented here is to create one governing (computerized) product definition to enable swift design and analysis iteration and optimization and to reduce redundant information among models.

A schematic of a current design process is shown in Figure 1. This process is characterized by several non-integrated domain-specific models that start from an idealized product (concept) definition, and conducts analysis that guides the synthesis of the product definition. If the synthesized concept fulfills the requirements the next product development step is started, otherwise the product concept design definition is updated and idealized for further analysis. This approach is time-demanding since the analysis activities are not efficiently integrated; optimization is typically conducted separately and sequentially and does thus not account for interactions.

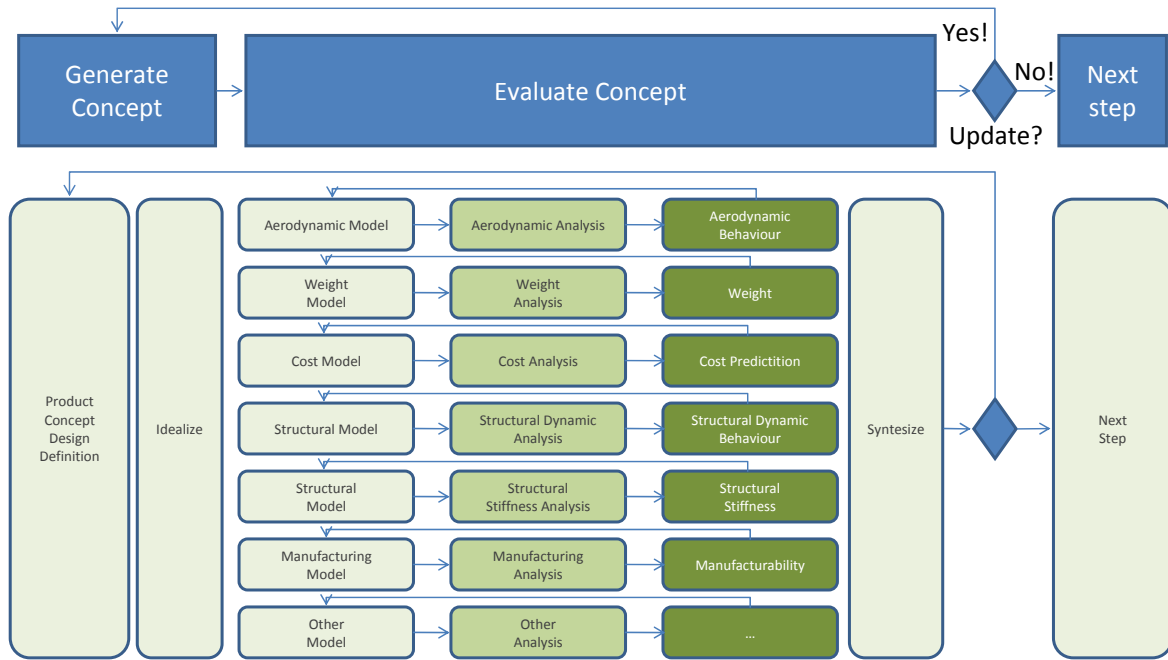


Figure 1. Current design process with parallel domain processes.

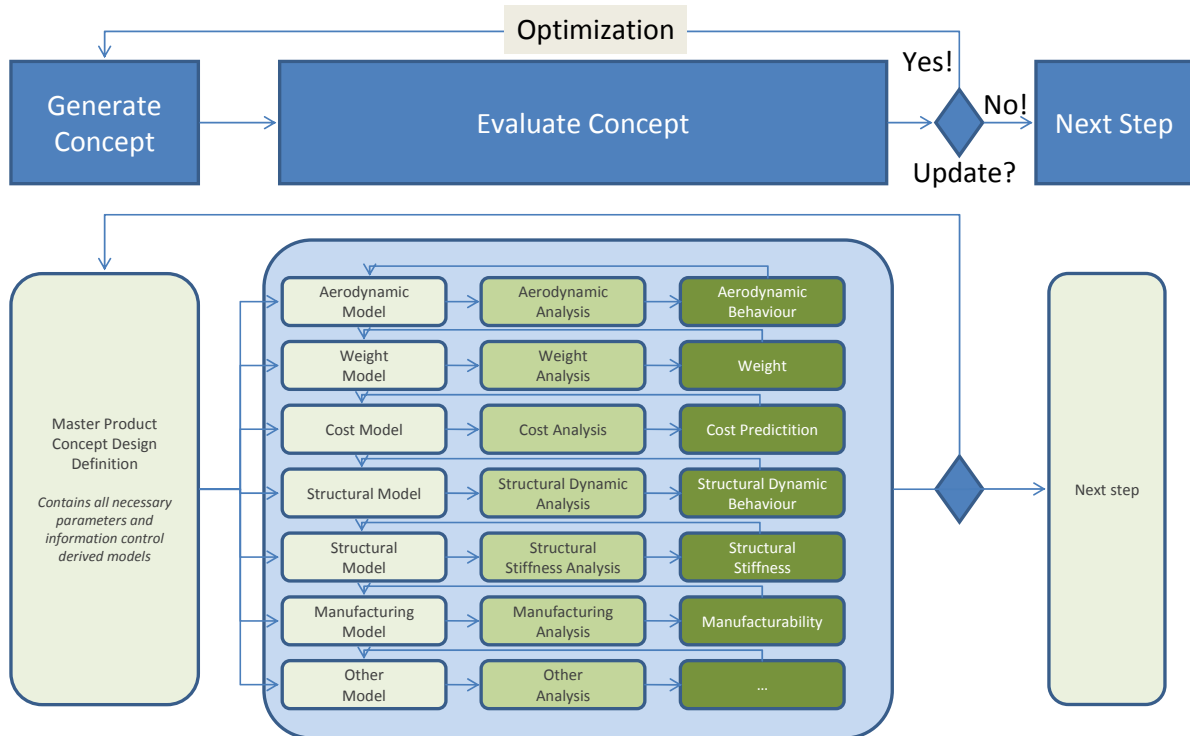


Figure 2. A schematic of the implications of the MM approach on the current design process.

The MM approach dictates that all governing information necessary to generate derived models necessary for domain analyses is stored and managed in one single context. The MM approach aims at controlling the integrated multi-disciplinary design and evaluation (i.e., optimization) process. The current design process would then be transformed into the process shown in Figure 2. Analysis input is extracted from the master product concept design definition. Examples of extracted information are geometry parameters, load cases and constraint. Each analysis can govern the change of the product definition one at a time or together. Other analyses can then reach an updated product definition and let its results update the product definition further. When an optimal design definition is

reached, preferable govern by an optimization algorithm, the loop is finished and next product development step takes place. The interaction can be partly semi-automated (interactive) or fully-automated governed by rules and macro-commands.

The consequences are that the derived models need to be automatically generated since optimization iterations need to generate a large number of domain specific models simultaneously. The principles of master models are simple, stating that redundant information should be avoided, i.e. that all information that characterizes the product definition, including common loads, constraints, material information etc. should be maintained within a single context.

6. Example

6.1. Application overview

A “pilot” application of a whole engine model has been implemented using the KBE module and the Advanced Simulation module of the CAD/CAE software Siemens PLM NX (Version 5) and Mathworks Matlab, [19]. An overview of the model input and output is shown in Figure 3.

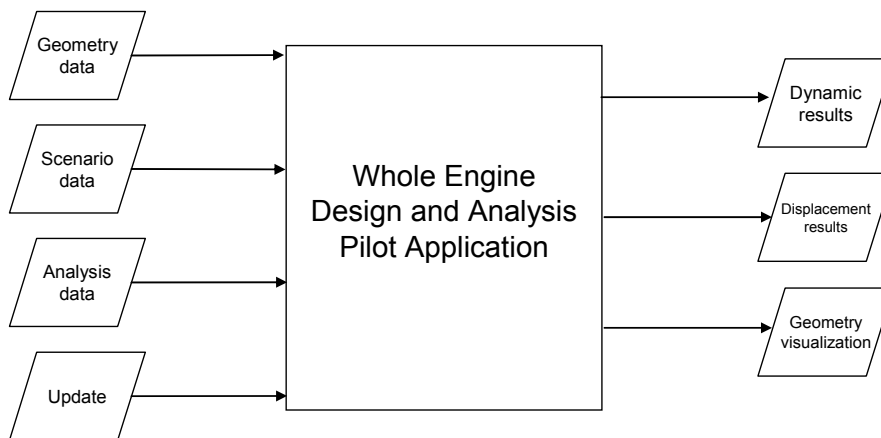


Figure 3. Overview of model input and output.

The geometry, scenario and analysis data is input through a GUI created in the UI styler module of NX. Geometry parameters (see Figure 4) consist of:

- Fan case length, thickness and radius
- Number of guide vanes for frames (front and rear)
- Cone angle

Scenario data consist of:

- Rotation speed
- Material
- Load case

Analysis data refers to

- Mesh data (mesh type, number of nodes)
- Constraints

The “update” input refers to maintaining the contents of the pilot application by changing the implementation by adding for example new geometry configuration possibilities. Dynamic results are forces and displacements due to rotational dynamics. Displacement results are the displacement caused by the dynamic forces. Geometry visualization is the function of showing a 3D view of the product – a standard function offered by the CAD software. Figure 5 depicts the component diagram of the application; the rule-base control governs both the geometry generation and the analysis interactions. The geometry generation is divided into three classes namely: fan case, frames and mount lugs.

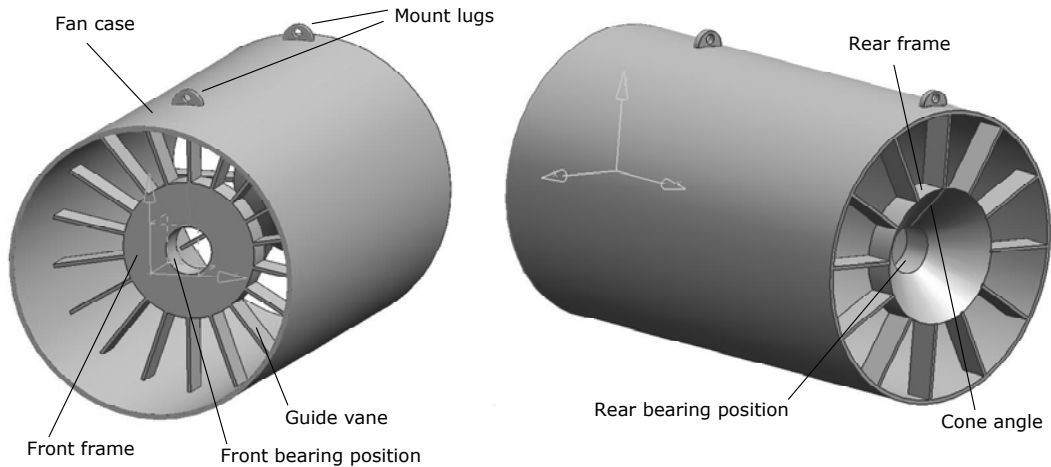


Figure 4. Geometry parts.

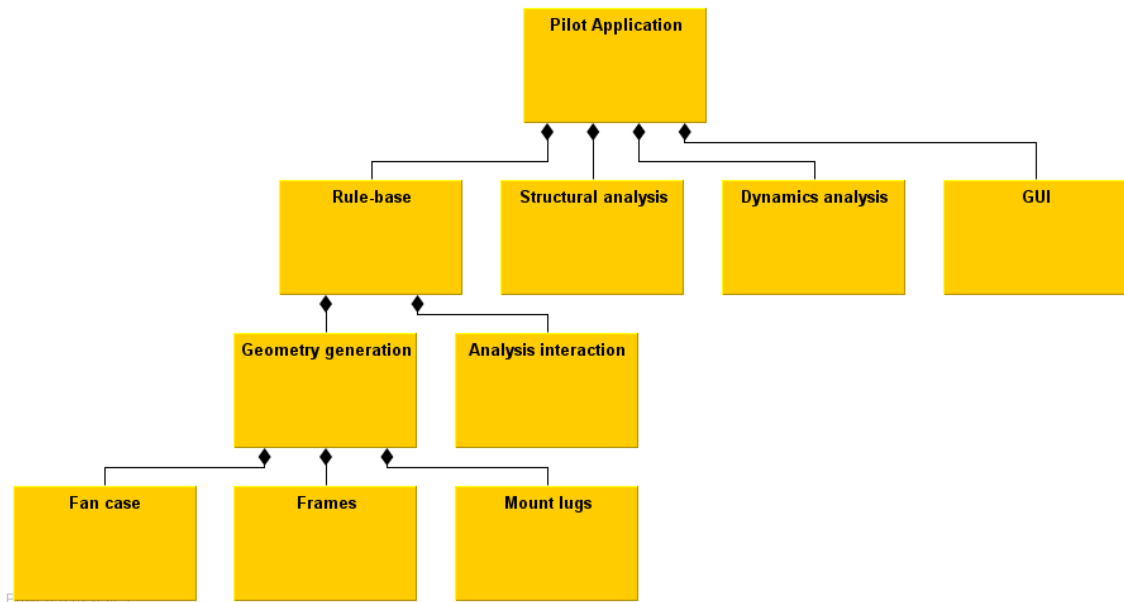


Figure 5. Application component diagram.

The activities included in the pilot application are shown in Figure 6. The activities are grouped into design, dynamics analysis and displacement analysis.

Design

In the design activities the geometry of the product definition is created. Input consists of geometric data (e.g. number of guide vanes, bearing position, fan case radius), scenario data and analysis data. Then an *Automatic generation of geometry* event takes place, controlled by the implemented parametric relations and rules in the KBE module.

Dynamics analysis

In the dynamics analysis activity the flexibility matrix for the geometry is calculated using NX, NX Nastran and Microsoft Excel. Then the flexibility matrix is used to calculate time dependent forces due to rotational dynamics. *Automatic preprocessing* includes meshing and applying constraints the geometry, controlled by the implemented rules executed by the KBE module. Then two manual steps take place: the first is *Manual meshing*, which includes creating a so-called spider-mesh at the shaft centre for each of the two bearings (front and rear); the second is *Manual loading*, which applies a unit force on the central node of the spider mesh. The problem is then solved and the displacements are collected in a spreadsheet. When all 16 components are collected the dynamic forces are

calculated in Matlab. If the dynamic forces are not higher than a guiding force limit set by experienced engineers the displacement analysis follows, otherwise the user returns to *Give input to Master Model* to change the input.

Displacement analysis

The displacement analysis activity includes applying the dynamic forces on the mesh in NX, solving and plotting time dependent displacements. If the analysis results indicate that the design satisfies the requirements the application activities end, otherwise the user goes back to *Give input to Master Model*.

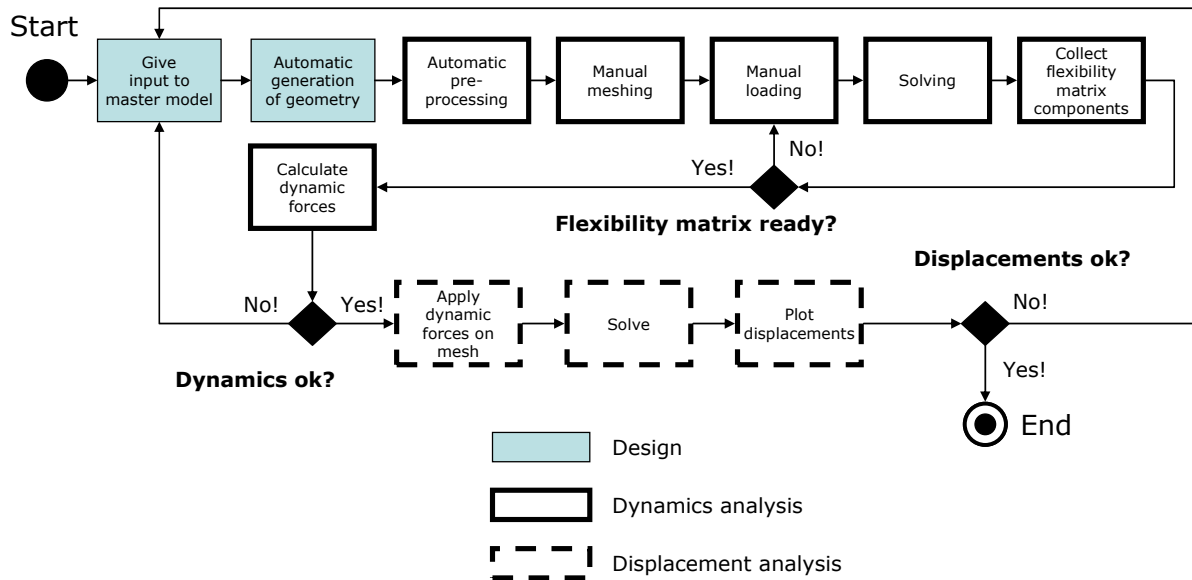


Figure 6. Activity diagram of the pilot application.

6.2. Scenario

The scenario considered here is a relocation of the rear bearing position. Figure 7 show an example of an automated geometry change, where the rear bearing position (or shaft length) is changed by modifying the cone angle of the rear frame. The loading case represents a fan blade off event as described in Section 6.3. The engine is constrained with fixed translation and rotation at the mount lugs, see Figure 4.

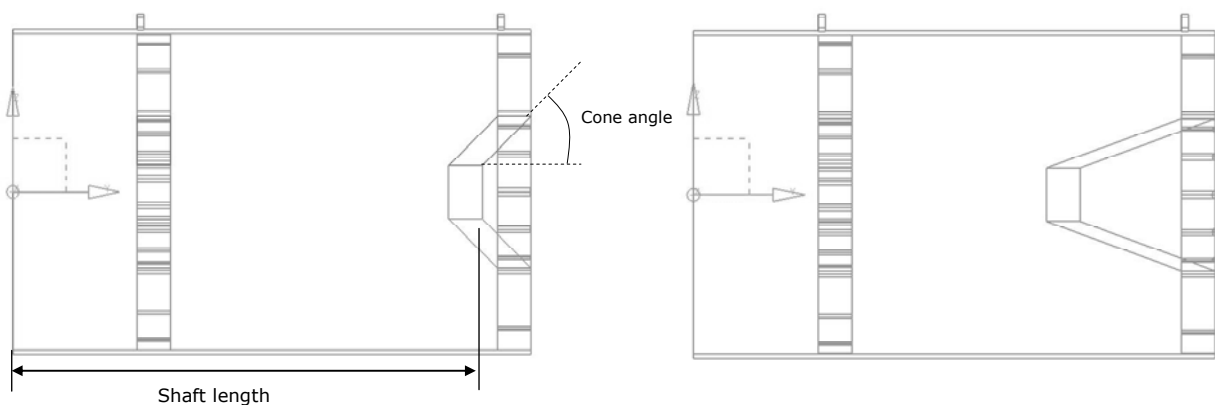


Figure 7. The cone angle is changed from 45 degrees to 20 degrees.

6.3. Models

The MM is implemented in the CAD/CAE software Siemens PLM NX5. Geometry generation and automated pre-processing is governed by rules in a hierarchy of object-oriented classes managed by the KBE module. The included geometry represents a simplification of the most crucial structural components of a civil turbo-fan jet engine. The design of the components between the front and the rear frames (Figure 7), e.g., compressors and turbines, is driven by aerodynamics and since aerodynamics are not considered in this pilot application the components are merely represented as simplified cylinders in the rotordynamic analysis. The finite element pre-

and post-processing is also done in NX5 but problem solving is done in NX Nastran.

In the rotordynamical model the turbine is simplified to a shaft with cylindrical beam elements. Two main components are included namely the fan and the compressor. The turbine interacts with the casing through the bearing positions which are described by coupled flexibility matrices found from the NX5 structural model. The rotordynamical analysis is done using an in-house Matlab code. In all simulations the studied load case is an unbalance in the fan which simulates the lack of one fan blade.

6.4. Results

An illustrative design problem has been defined where the goal is to find a cone angle for the rear frame that minimizes both the maximum displacement (see Figure 8 for example displacement plot) and the mass for the engine. Reducing the cone angle implies reducing the shaft length (bearing position) and therefore the mass of the jet engine.

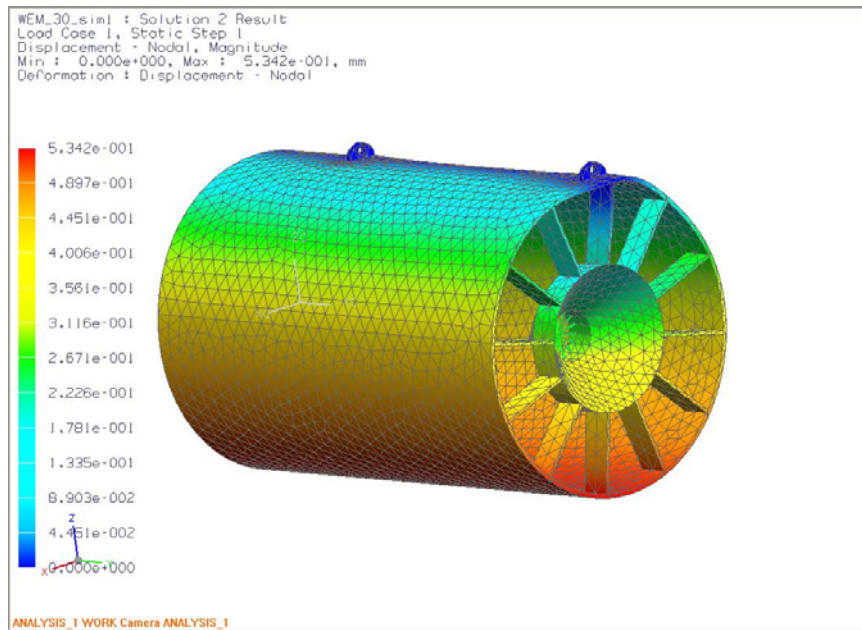


Figure 8. Example displacement results for the 40 degree cone angle.

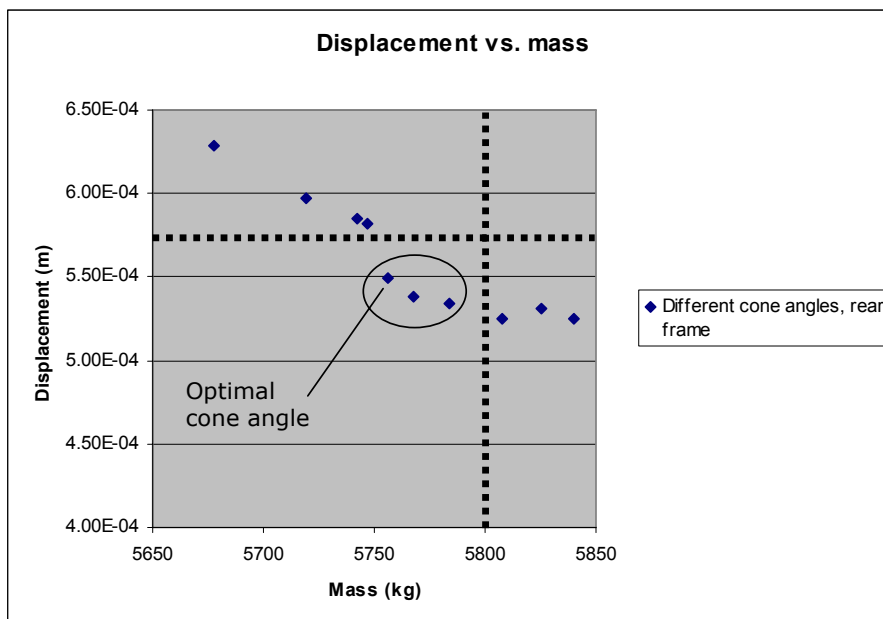


Figure 9. Maximum displacement versus mass of jet engine.

Figure 9 depicts the quantified tradeoff between (maximum) displacement and mass due to different bearing positions, obtained using the pilot MM application. Each point in Figure 9 represents a different bearing position (i.e., design) created by manually altering the cone angle input (20, 25, 29, 30, 32, 40, 50, 60 and 70 degrees) to the GUI, see *Give input to master model* in Figure 6. The constraint boundaries for maximum allowed displacement and mass is illustrated by the dotted lines. Of the ten designs only three fulfill the requirements and one is found optimal since that design minimizes the mass without violating the displacement constraint.

4. Discussion

A master-model (MM) approach for whole jet engine analysis and design optimization has been presented and exemplified with a pilot application. Compared to other approaches (see, e.g., [2-4]) the MM approach focuses on the following features. A first objective is to enable each analysis to update the design separately instead of only having one main iteration loop as in the wing example of [4]. Secondly, automation is important to enable swift multidisciplinary optimization. Therefore *both* automation of geometry generation, as also in [4], and preprocessing, as also in [3], are targeted in the MM approach and exemplified in the pilot application. The MM approach also aim for integration of any model, see Figure 2, instead of focusing on a subset such as structural and aero dynamical analysis as seen in [2]. The results from the pilot analysis session show that it is possible to use the MM pilot application to conduct trade off analyses to find optimal designs.

The KBE-based MM approach has been developed with the objective to be integrated into a decomposition-based design optimization methodology. Specifically, we will utilize the MM framework to conduct analytical target cascading (ATC) optimization studies. ATC is a rigorous, mathematical systems engineering methodology developed to support decomposition-based design optimization activities [20]. An optimization problem is formulated and solved for each element of a decomposed system to minimize deviations of local responses from propagated targets. Solving the subproblems using appropriate coordination strategies yields overall system optimality, i.e., satisfying design targets as close as possible under the given resources, and consistency, i.e., ensuring system integration. In this manner, ATC can be used to quantify component interactions and assess the impact of component design on system level attributes quantitatively, so that component design specifications can be determined consistently to satisfy system-level design targets. The ATC methodology has convergence properties [21] and has been enhanced, extended and applied continuously and extensively over the past years, see, e.g., [22-24].

To further reduce lead times in the application, it is important to automate activities currently conducted manually, e.g., the flexibility matrix creation. There is also an interest to further validate and develop the MM approach by including other analysis activities such as aerodynamics, cost, manufacturability, etc in the pilot application.

4. Conclusion

A master-model (MM) approach to enable integrated analysis and design optimization of whole jet engines in the early design phase has been proposed. The idea is to create one product definition that can be used to interact with all analyses. Each analysis activity can automatically extract the needed information and then use results to guide further product definition changes. The MM approach was exemplified with a simple yet illustrative industrial application, where a whole jet engine structure is designed by analyzing dynamics forces due to a fan blade off event and the resulting displacements due to the dynamic forces. Compared to other approaches it is argued that the contribution of the proposed MM approach lays in:

- The novel capability of iterating the product definition after each analysis
- aiming at full automation to enable swift multidisciplinary design optimization
- aiming at integration of any analysis model

5. Acknowledgements

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