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A Knowledge-based Master-model Approach with Application to Rotating Machinery Design

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Abstract: Novel rotating machinery design concepts and architectures are being explored to reduce mass, energy consumption, manufacturing costs, and environmental impact while increasing performance. As component manufacturers supply parts to original equipment manufacturers, it is desirable to design the components using a systems approach so that they are optimized for system-level performance. To accomplish that, suppliers must be able to model and predict the behavior of the whole machinery. Traditional computer-aided design/computer-aided engineering master-modeling approaches enable manual changes to be propagated to linked models. Novel knowledge-based master-modeling approaches enable automated coordination of multidisciplinary analyses. In this article, we present a specific implementation of such a knowledge-based master-modeling approach that facilitates multidisciplinary design optimization of rotating machinery. The master-model (MM) approach promotes the existence of a single governing version of the product definition as well as operating scenarios. Rules, scripts, and macros link the MM to domain-specific models. A simple yet illustrative industry application is presented, where rotor-dynamics and displacement analyses are performed to evaluate relocation alternatives for the rear bearing position of a rotating machinery under a 'fan-blade-off' load case.

Key Words: rotating machinery, knowledge-based engineering, master-models, multidisciplinary analysis and design optimization.

1. Introduction

During early design, it is crucial to account for the product life-cycle when making important decisions. Integrated product development (also known as concurrent engineering) is one approach used to address this challenge [1,2]. In the rotating machinery industry (e.g., jet engines or stationary gas turbines), design objectives include reducing mass, fuel consumption, and manufacturing costs while increasing performance. Reducing environmental impact is an additional, and increasingly important, design objective [3]. Novel machinery design concepts and architectures are being explored to achieve these design objectives. Manufacturers who supply parts to original equipment manufacturers (OEMs) will enjoy a competitive advantage if they can design their components using a systems approach that optimizes components for system-level performance.

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Figures 1, 2 and 5–7 appear in color online: http://cer.sagepub.com

Several issues hinder such a systems approach in current practice. Continuous updates by the OEMs in the configuration and design at the system level are not readily available to suppliers. At the same time, machinery components must be optimized to satisfy design targets that are set at the system level. Moreover, the component manufacturers have access to machinery system and component models of variable fidelity. Therefore, there is a need to model component behavior in the rotating machinery system context: component manufacturers need models that link system-level product definitions to component-level design and analysis activities. One way of addressing this challenge is to create master models (MM) that automatically link the different models [4–6].

The goal of our research is to develop and implement an efficient automated multidisciplinary design and analysis approach that does not involve unnecessary product definition updating tasks, and to contribute to the literature body that focuses on managing product definition changes that occur when domain-specific models are concurrently used for different analyses. Such an approach would facilitate crossing disciplinary

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boundaries within an enterprise. Specifically, this article presents a knowledge-based MM approach to integrated design and analysis of structural rotating machinery that features effective information management. The MM approach aims at minimizing information being stored at multiple sites; 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 MM changes. Another analysis activity can then access updated information, and its results guide further updates of the MM. In this manner, the product representation is updated during the multi-disciplinary design optimization process.

A simple yet illustrative example is presented where dynamics and displacement analysis are performed using the MM. The integrated analysis and design optimization framework is used to examine 'what-if' scenarios rapidly. The scenario examined here evaluates rear bearing position relocation alternatives, where a load case of rotating mass imbalance due to a 'fan-blade-off' event (lost fan blade) is considered. The design objectives include minimizing displacement and mass. The presented implementation constitutes an additional demonstration of the feasibility of the MM approach for the rotating machinery application domain, and contributes to the development of a MM approach that integrates demand-driven knowledge-based engineering (KBE) capabilities with computer-aided design (CAD) software capabilities.

2. Knowledge-based Engineering

KBE is a fundamental concept of the MM approach proposed in this article. Stokes defines KBE as *the use of advanced software techniques to capture and re-use product and process knowledge in an integrated way* [7]. Automating chains of engineering activities is not new; this has been used by engineers since the early developments of computer-aided modeling and simulation [8–10]. According to reference [11], KBE was first coined at the launch of the CAD software ICAD. The popularity of KBE increased during the 1990s and 2000s when useful mechanical engineering applications were reported, see e.g., [12–15]. KBE aims at making engineering design more effective by (i) automating routine and time-demanding tasks by formalizing captured explicit knowledge into rules and (ii) showing design change implications on downstream activities, e.g., cost, manufacturability, maintainability, etc. The functionality of commercial KBE software is often based on automating mechanical CAD; KBE-modules coupled to CAD-packages include Siemens PLM NX and Dassault Systems Catia [16,17]. KBE applications for automatic finite element pre- and post-processing have been reported in references [18,19].

Kessler presented a generic framework for multi-disciplinary design optimization (MDO), which uses an Integrated Design Model to integrate numerous analyses [20]. The framework is exemplified for jet engine design and analysis, where the geometry is generated through a knowledge-based engineering module and optimized for thermal, stress, and lifing objectives. The approach presented in reference [20] has manual pre-processing, i.e., meshing and loading as well as design and analysis are conducted in one main iteration loop; however, the product definition is not updated after each analysis during the MDO process. The MM approach, proposed in this article, has automated pre- and post-processing to integrate design and analysis and enable optimization.

A strategy for automated aircraft design has been reported by Hwang et al. [21]. The MM approach, proposed in this article, deals with information management strategies and CAD-based product definitions. The data are handled using several databases, and CAD software is programmed through an application programming interface (API). A graphical user interface (GUI) was created using C++ to aid inexperienced designers. Aerodynamics, mass, stability and control, propulsion, and performance analyses were considered. The geometry generation is semi-automated; one limitation of the approach presented in reference [21] is that designers manually search for relevant aircraft configuration solutions according to the task at hand.

Lee presented a CAD–CAE (computer-aided engineering, CAE) integration strategy for feature-based design [22]. It is exemplified for a simple geometry and can vary both in dimensions (e.g., 1-D, two-dimensional (2-D), and 3-D) as well in detail. The strategy is based on a MM that creates the required CAD and CAE models. CAD model creation is done interactively with the user. The abstraction and dimensional function is semi-automatic. Since the Lee framework is not fully automatic, further work is needed to use it in an optimization loop.

An optimization model and analysis environment for joint-wing configuration were presented by Rasmussen et al. [6]. A geometric model was converted into a finite element model for aerodynamic and structural analyses using KBE software.

Röhl et al. [5] presented a web-based environment for linking distributed product models. A so-called Intelligent MM was created for multidisciplinary optimization purposes by combining CAD MM techniques with KBE. The environment is exemplified with a turbine blade mechanical analysis where geometry is generated, meshed, boundary conditions are added, and then the finite element problem is solved.

La Rocca and van Tooren [4] presented a framework to enable MDO supported by KBE. The core unit of the system consists of a multi-model generator (MMG) that can generate numerous aircraft component (exemplified with an aircraft wing) configurations based on a high-level primitive concept. The MMG can 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.

This article contributes an additional MM implementation of the KBE approach to the aforementioned literature body to demonstrate the practical usefulness of such approaches for multidisciplinary analysis and design of rotating machinery.

3. The Knowledge-based MM Approach

MM approaches aim at creating a geometry representation that can be used for CAD, computer-aided manufacturing, and CAE. Every change in the geometry representation is automatically propagated to all domain-specific models. One of the first MM approaches was reported by Newell and Evans [23]; a number of researchers have elaborated the MM approach since, e.g.: Hoffman and Joan-Arinyo [24] suggested an MM architecture centered around a server and a repository to which different clients can connect to. These clients can be CAD systems, geometrical dimensioning and tolerancing agents, manufacturing process planners, or other downstream clients. Each client receives their view of the design. Each design change made by one of the clients causes changes to other clients' views according to a change protocol and permissions. The architecture is semi-automated and user interaction needed.

The MM approach presented in this article uses a single governing (computerized) product definition to enable swift design and analysis iterations while reducing information overhead among analysis models by combining KBE demand-driven capabilities with CAD software capabilities. The current product development process is characterized by several non-integrated domain-specific models that manually generate a product concept design definition based on OEM input, e.g., stiffness, performance, geometry, weight, etc., in early product development stages. The concept may be generated as a multidisciplinary effort (by teams of structural engineers, aerodynamics engineers, CAD engineers, etc.), but when it comes to analyzing the concept, it is often the case that several different product definitions are created in parallel. One reason for this is that each domain has its own analysis models and modifies them to represent a new concept. For example, a new structural model may be created by modifying previous models through mesh morphing and cut-and-paste. Models are often idealized, and less important geometry (e.g., small holes, blends, etc.) is not included. Hence, the geometry only includes the vital function of the product definition. One reason for the product definitions being different is that analysis engineers may find that the main concept fails a certain analysis and start testing other concept ideas. By the time the multidisciplinary team reconvenes for synthesis, a number of different new concepts may have been generated. Since the new concepts have not been evaluated against all necessary analyses, the models have to be modified again. This approach is quite time-consuming since the analysis activities are not efficiently linked to the main product concept definition. There exist several product definitions; optimization is thus conducted separately and sequentially, and does not account for interactions.

The principles of MMs 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. In other words, the MM approach dictates that all governing information necessary to generate domain-specific models is stored and managed in one single context. By generating models, it is meant that a model is created in the tool environment that the analysis engineer uses, as also mentioned in reference [4]. The schematic of the knowledge-based MM design process is shown in Figure 1. Each sub-model needs input and generates a controlled set of output, whereas each individual sub-model (trace in the figure) can rely on either demand-driven or procedural techniques for model generation and analysis.

The MM generates a governing product concept definition based on input given by a design team. This input is based on information made available by the OEM. Rules manage the concept generation as well as the analysis model generation. The analysis model generation is based on MM information, e.g., geometry features and parameters, load cases, stiffness matrices, mass matrices, and constraints. In this way, the MM generates domain-specific models at all decomposition levels of the product (system).

The generated analysis or simulation models can have different levels of fidelity depending on design needs. As system components are designed for system-level optimality, the MM manages the changes occurring in a model at any level (system, sub-system, component, part, etc.) by updating linked models at other levels accordingly. As component design variables are varied during optimization, the MM updates linked variables and parameters in all other models automatically (design variables are changed by optimization while design parameters are kept fixed during optimization; however, a quantity that is a design variable in the optimization

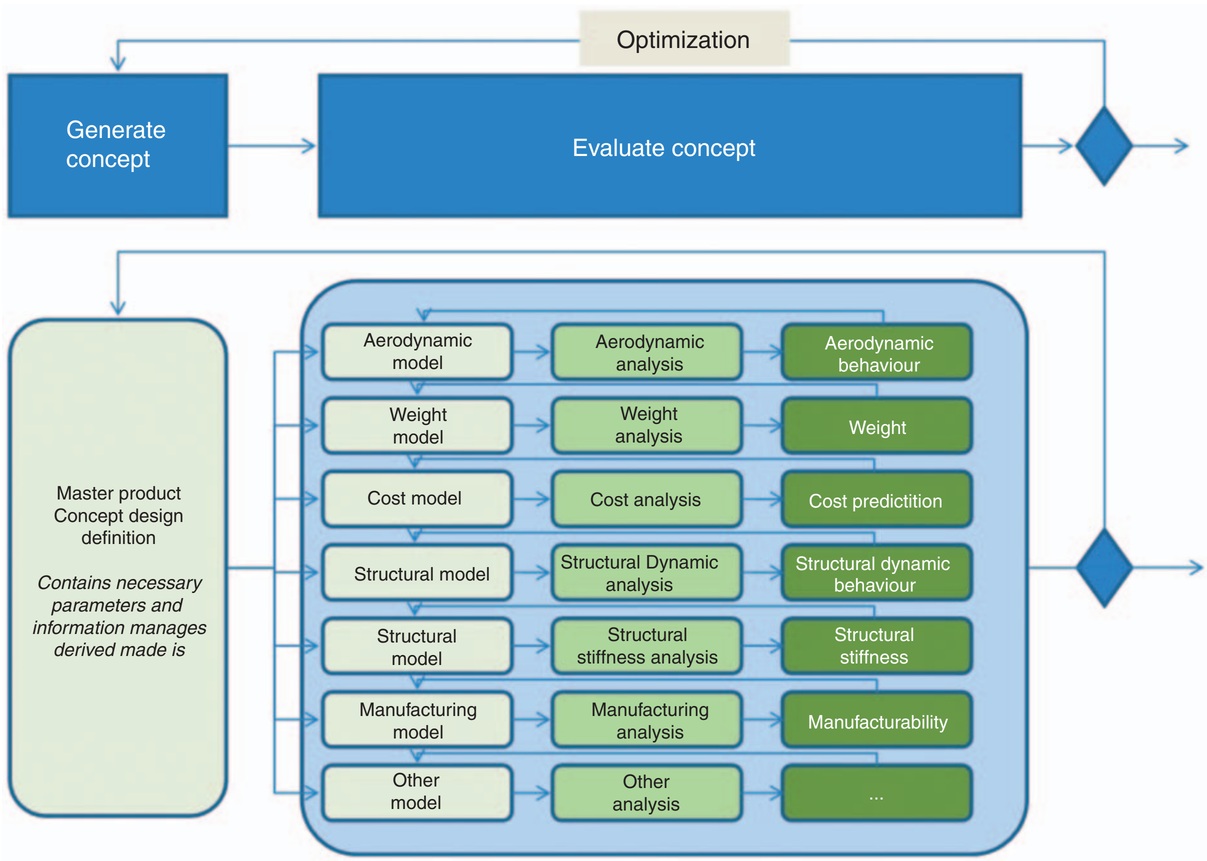

Figure 1. A flow chart of the design process using the MM approach.

problem associated with one component may be a design parameter in an optimization problem associated with another component, and *vice versa*). In this manner, other analyses can be conducted, and their results can guide product definition changes. Therefore, the analysis models are automatically generated and governed by rules, API commands, macro-commands, or scripts.

Object-oriented KBE software (such as knowledge fusion in NX) usually has predefined classes for fundamental geometry objects (e.g., block, cylinder, ellipse, datum-plane), predefined methods or functions for parameter handling (e.g., max, min, floor), and CAE operations (e.g., meshing, boundary conditions). The rules that govern the analysis model generation reside within the user-defined geometry classes within the KBE module of the CAD software. These classes use the predefined classes to create specific geometry, e.g., the rotation machinery exemplified in the following section. A number of parameters comprise object definitions inside each of these classes. These parameters are used to generate the analysis models. Functions within the KBE software can be used to trigger model generation, e.g., by submitting an input file to a solver. The input file can be created by either the KBE software or an external program (e.g., MATLAB or PYTHON) that is called by a function within the KBE software.

4. Whole Machinery Model Example

The MM proposed in this article is demonstrated using a simple yet illustrating example of an whole rotating machinery model, implemented using the KBE and advanced simulation modules of the CAD/CAE software packages Siemens PLM NX7 and MATLAB 2009.

4.1 Geometry and Mass Models

The geometry for the whole rotating machinery is generated by the KBE module and the geometry class hierarchy is presented in Figure 2 using the Unified Modeling Language [25]. The *Whole Rotating Machinery Geometry Class* generates the fan case, frames, and mount lugs. In each geometry class, a number of attributes are declared (a total of 41) and between the attributes relationships exists, e.g.:
guideVaneLength: fanCaseInnerRadius:-coneEndz: +fanCaseThickness:/2;

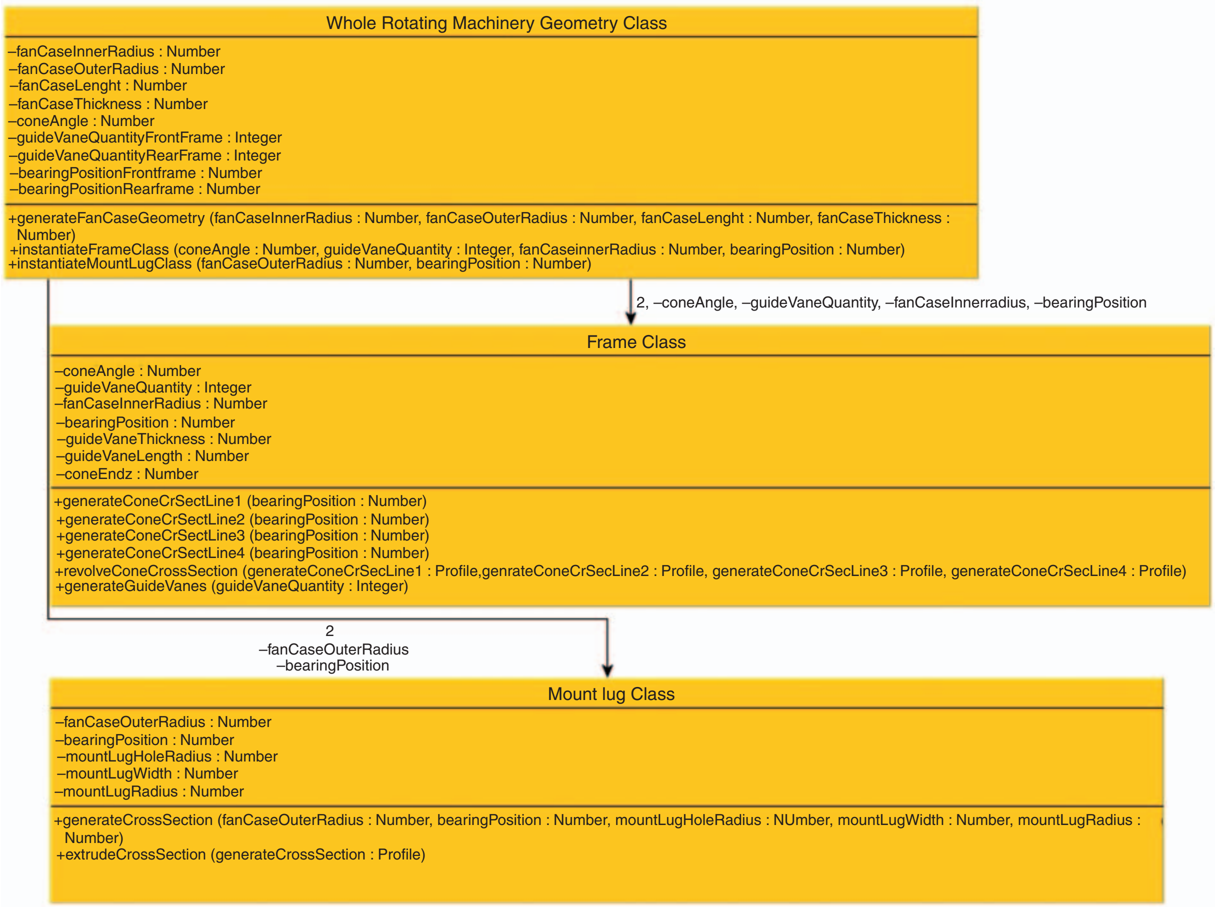

Figure 2. The rotating machinery geometry class hierarchy.

The attributes are used to generate the geometry objects (a total of 21) and the rotor-dynamics model. Given a configuration change of the whole rotating machinery model, only attribute values affected by that change are re-evaluated.

The included geometry represents a simplification of the most crucial structural components of rotating machinery such as an intermediate case and turbine rear frame, and is shown in Figures 3 and 4.

The architecture consists of a static part-fixed fan case connected to a fastening device *via* mount lugs and a rotating part.

The dimensioning of the static part is given by eight parameters L_1, L_3, d_1, d_2, d_3, θ, M_1, M_2, B_1, and B_2 as illustrated in Figure 4, where L_1 is the distance from a fan case edge to the first bearing edge along the y-direction, L_3 the fan case length along the y-direction, d_1 the bearing diameter (the same for both bearings), d_2 the fan case diameter, d_3 the difference between extreme rays of cone, θ the cone angle, M_1 and M_2 the mount lug coordinates along the y- and z-directions, respectively, and B_1 and B_2 the bearing coordinates along the y- and z-directions, respectively. L_2, shown in Figure 4, is the rotating shaft length and defined as a summary of the beam elements.

The design of the rotating components between the front and rear frames (compressors, turbines, fan, etc.) is driven by aerodynamics. In this article, we focus on structural dynamics; therefore, these components are represented in a simplified manner by cylinders with given lengths and radii in the rotor model shown in Figure 5, where the rotation is performed around the y-axis.

All the parameters are specified by a user except L_2, θ, and B_2, where θ is a design variable and L_2, B_2 are θ-dependent:

$$L_2 = L_3 - \tfrac{r_1}{tg\theta} \tag{1}$$

$$B_2 = L_2 - \frac{B_L}{2} \tag{2}$$

where B_L is the bearing length in the y-direction as specified by the designer. The mass of the whole machinery is defined as:

$$\text{Mass} = \text{Mass}_1 + \text{Mass}_2 \tag{3}$$

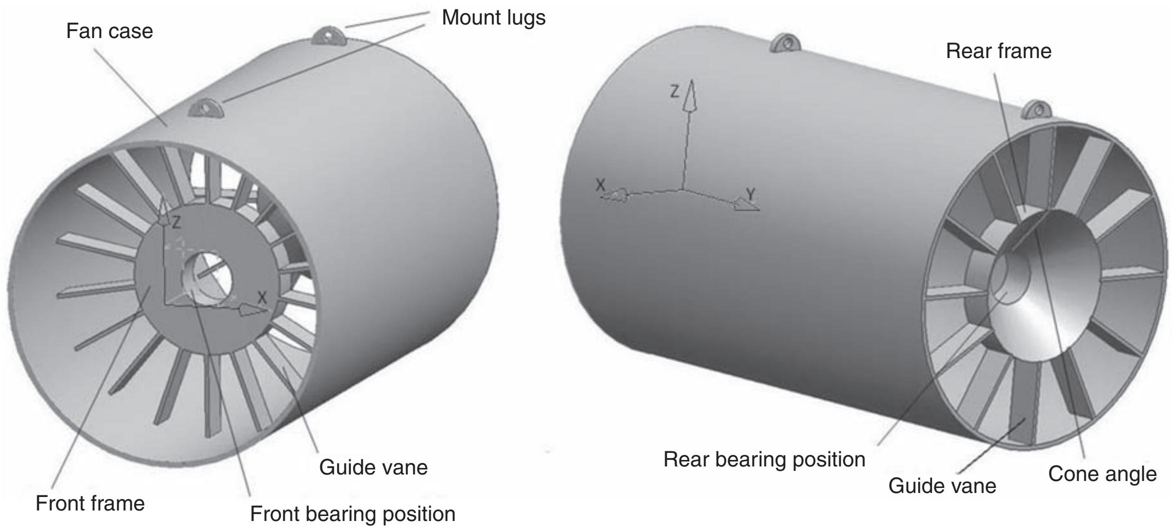

Figure 3. The simplified whole rotating machinery geometry generated in NX 7.0.

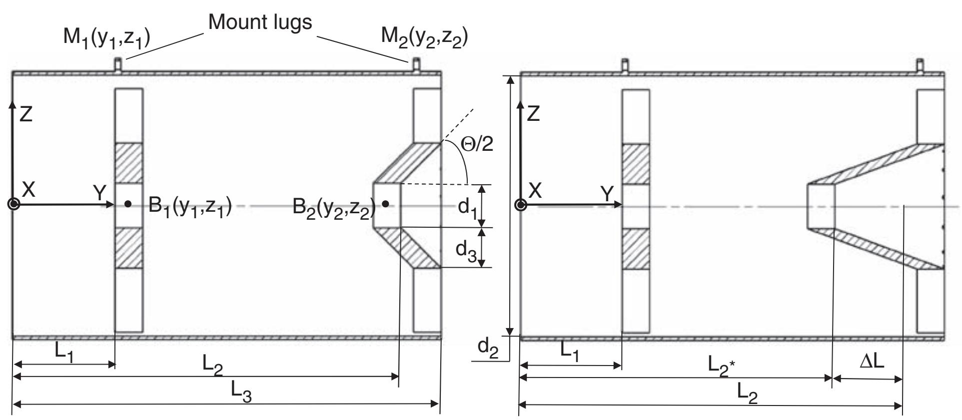

Figure 4. The initial design, where a cone angle is 90° (left); design where a cone angle is changed to 40° (right).

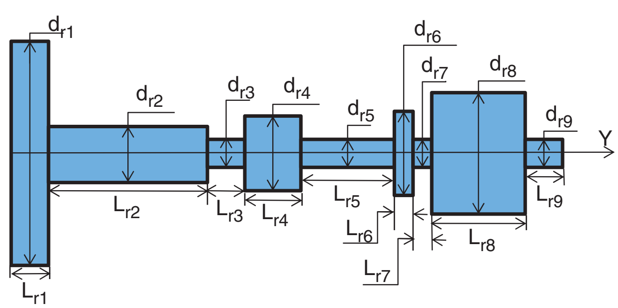

Figure 5. The cylindrical beam elements of the rotor-dynamics model.

where Mass_1 is the mass of the static part and Mass_2 the mass of the rotating part, calculated by

$$\text{Mass}_j = \sum_{i}^{n_j} V_i \rho_i,\ j{=}1{,}2 \tag{4}$$

where V_i is volume and ρ_i density of each element i of the static part, such as case fan, guide vanes, and cones, and each i – beam element of the rotor. The number of elements n_j depends on the design details.

4.2 Rotor-dynamics and Displacement Analysis

In the static analysis, the stiffness matrices for a particular geometry are calculated using NX Nastran (bearing stiffness matrix) and MATLAB (global stiffness matrix). The rotating parts interact with the static structure through the bearing positions, which are described by the coupled flexibility matrix (inverted bearing stiffness matrix) $\mathbf{K}_b^{-1}$. Both stiffness matrices are used to calculate time-dependent forces due to rotational dynamics. Automatic pre-processing includes meshing and the formulation of geometry constraints, controlled by the implemented rules (or relationships between the attributes) in the KBE module and NX journals.

The classes for pre-processing have 42 attributes and 14 CAE objects. The finite element model consists of nearly 250,000 degrees of freedom and uses solid tetrahedral elements. The meshing part generates a solid mesh and adds the nodes to couple the static structure and rotating part. The solid mesh and nodes are created by KBE rules. A spider-mesh at the shaft center for each bearing (front and rear) is also created to connect the central nodes to the solid mesh. Translation in two directions (x and z) for each coupling node (bearing position) is included in the bearing stiffness matrix.

The user specifies material (density ρ), modulus of elasticity (E), length (L_r), and diameter (d_r) for each beam element of the rotor. In this article, the rotor consists of 9 elements (10 nodes), generated by a KBE class which use the attributes from the geometry classes, (the class that generates the rotor model has 50 attributes) and is described by stiffness ($\mathbf{K}$), nodal mass ($\mathbf{M}$), and nodal gyroscopic ($\mathbf{G}$) matrices. Each node connects two beam elements. The nodal stiffness and gyroscopic matrices for the nodes $j = 1,..,10$ are given by

$$\mathbf{M} = \begin{bmatrix} M_1 & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & M_{10} \end{bmatrix}, \mathbf{G} = \begin{bmatrix} G_1 & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & G_{10} \end{bmatrix} \text{ where}$$

$$\mathbf{M}_j = \begin{bmatrix} m_{1j} & 0 & 0 & 0 \\ 0 & m_{2j} & 0 & 0 \\ 0 & 0 & m_{3j} & 0 \\ 0 & 0 & 0 & m_{4j} \end{bmatrix}, \mathbf{G}_j = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & J_{pj} \\ 0 & 0 & -J_{pj} & 0 \end{bmatrix},$$

$j = 1,2,\ldots,10$, with

$$m_{1j} = m_{2j} = \frac{m_k + m_{k+1}}{2},$$
$$m_{3j} = m_{4j} = \frac{m_k}{2}\left(\frac{d_k^2}{16} + \frac{L_k^2}{12}\right) + \frac{m_{k+1}}{2}\left(\frac{d_{k+1}^2}{16} + \frac{L_{k+1}^2}{12}\right),$$
$$\text{and} \quad J_{pj} = \frac{J_{pk} + J_{pk+1}}{2}$$

The node $j = k+1$ connects beam elements k and k+1. Note that if $k = 0$ or $k = 11$, then the mass (m_k), diameter (d_k), length (L_k), and polar mass of inertia (J_{pk}) of a given node are equal to zero. The stiffness matrix for each beam element i is given by

$$\mathbf{K}_i = \begin{bmatrix} \alpha_i & \beta_i \\ \gamma_i & \delta_i \end{bmatrix}$$

where

$$\alpha_i = \frac{E_i I_i}{L_i^3}\begin{bmatrix} 12 & 0 & 0 & 6L_i \\ 0 & 12 & -6L_i & 0 \\ 0 & -6L_i & 4L_i^2 & 0 \\ 6L_i & 0 & 0 & 4L_i^2 \end{bmatrix},$$
$$\beta_i = \frac{E_i I_i}{L_i^3}\begin{bmatrix} -12 & 0 & 0 & 6L_i \\ 0 & -12 & -6L_i & 0 \\ 0 & 6L_i & 2L_i^2 & 0 \\ -6L_i & 0 & 0 & 2L_i^2 \end{bmatrix},$$
$$\gamma_i = \frac{E_i I_i}{L_i^3}\begin{bmatrix} -12 & 0 & 0 & -6L_i \\ 0 & -12 & 6L_i & 0 \\ 0 & -6L_i & 2L_i^2 & 0 \\ 6L_i & 0 & 0 & 2L_i^2 \end{bmatrix},$$
$$\delta_i = \frac{E_i I_i}{L_i^3}\begin{bmatrix} 12 & 0 & 0 & -6L_i \\ 0 & 12 & 6L_i & 0 \\ 0 & 6L_i & 4L_i^2 & 0 \\ -6L_i & 0 & 0 & 4L_i^2 \end{bmatrix},$$

with $I_i = \frac{\pi d_{ri}^4}{64}$. The global stiffness matrix $\mathbf{K}_{wb}$ (without bearing stiffness) is defined as

$$\mathbf{K}_{wb} = \begin{bmatrix} \alpha_1 & \beta_1 & 0 & \cdots & & 0 \\ \gamma_1 & \delta_1 + \alpha_2 & \beta_2 & \cdots & & 0 \\ 0 & \gamma_2 & \delta_2 + \alpha_3 & \cdots & & 0 \\ 0 & 0 & \vdots & \ddots & & 0 \\ \vdots & \vdots & & & \delta_{i-1} + \alpha_i & \beta_i \\ 0 & 0 & 0 & 0 & \gamma_i & \delta_i \end{bmatrix}$$

In the last stage of the static analysis, the elements of the bearing static matrix $\mathbf{K}_b$ (as computed using NX Nastran) are added to the corresponding elements of the global stiffness matrix $\mathbf{K}_{wb}$.

The rotor-dynamics analysis is conducted in MATLAB to calculate the maximum dynamic forces. A general rotor-dynamic equation $[\mathbf{M}]\ddot{r} + \Omega[\mathbf{G}]\dot{r} + [\mathbf{K}]r = \mathbf{F}$ is solved using Taylor expansion, where the maximum elements of position vectors $\mathbf{r}_x$ and $\mathbf{r}_z$ are found. In this article, the rotational speed Ω equals 200 rad/s, and the 2-D time-dependent force vector $\mathbf{F}$ is defined as:

$$\mathbf{F} = m_e\Omega^2\begin{bmatrix} \cos(\Omega t) \\ \sin(\Omega t) \end{bmatrix}$$

where m_e is the mass eccentricity. In the last stage, the maximum bearing forces $\mathbf{F}_{\max}$ are calculated to simulate an unbalanced rotation using the relation $\mathbf{F}_{\max} = \mathbf{K}_b\begin{bmatrix} r_{x1\max} & r_{x2\max} & r_{y1\max} & r_{y2\max} \end{bmatrix}^T$.

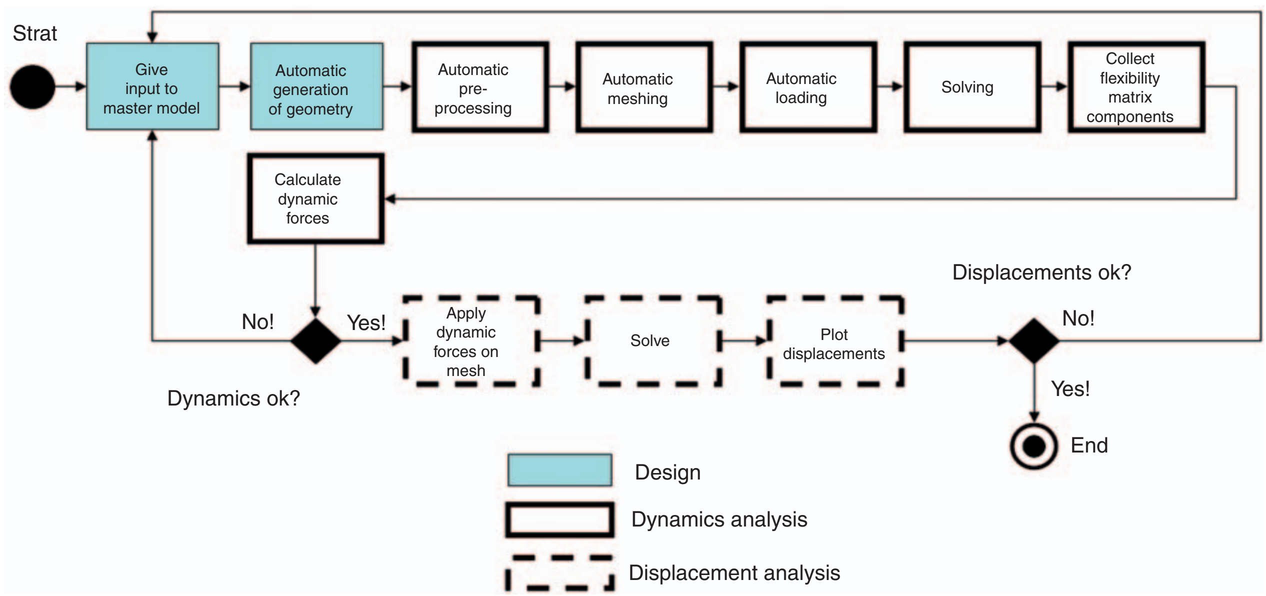

Figure 6. Design and analysis activity diagram.

The rotor-dynamics results are input to the NX 7 post-processing navigator and the maximum displacements are found. The displacement analysis is conducted in NX Nastran for the maximum load that occurred during the rotor-dynamics analysis. If the analysis results indicate that the design satisfies the user's requirements, the application activities stop; otherwise, the design (in this case represented by the cone angle) is updated.

4.3 Design Change Scenario

The design change scenario considered in this article is a relocation of the rear bearing position (B_2) along the y-direction, as depicted in the machinery cross-section shown in Figure 4. In Equations (1) and (2), the rear bearing position is linked to the shaft length and cone angle. Hence, if the rear bearing position along the y-direction is changed, then the cone angle is modified. The loading case emulates a 'fan blade off' event, i.e., the rotating imbalance caused by the loss of a fan blade. The machinery is constrained with fixed translation and rotation at the mount lugs.

Activities are grouped into design, dynamics analysis, and displacement analysis, as shown in Figure 6. The geometry of the product definition is automatically created based on the input *via* the GUI and controlled by the rules in the user-defined classes. NX journals, which are recordings of NX sessions, have been used to automate activities that the KBE classes could not manage to automate but also to launch the KBE classes. Using a NX menu-file, all journals are fired in a sequence creating the flow of activities shown in Figure 6.

The goal is to define a rear frame cone angle to minimize both maximum displacement and machinery mass. Reducing the cone angle implies reducing the shaft length (rear bearing position along the y-direction, and therefore the mass of the whole machinery. Figure 7 depicts the quantified trade-off between maximum displacement and machinery mass for different rear bearing positions. Each rhombus represents a different bearing position caused by altering the rear frame cone angle input (20°, 25°, 29°, 30°, 32°, 40°, 50°, 60°, and 70°). The constraints on maximum displacement and mass are represented by dotted lines. Only 3 of 10 evaluated designs satisfy the constraints; of these three, we consider the design that minimises the mass without violating the displacement constraint as an optimal one.

5. Concluding Remarks

A MM approach for a simplified rotating machinery analysis and design optimization has been presented and demonstrated in this article. The MM approach uses a single central product definition to manage the models required in various analysis activities. Each analysis activity extracts required information automatically, and uses the results to guide further product definition changes. This article presents the development and implementation of a MM approach that integrates demand-driven KBE capabilities with CAD software capabilities. While the objectives are similar to the ones of the generative KBE tools from the 1980s and the 1990s, the aim is to ensure control of a defined design

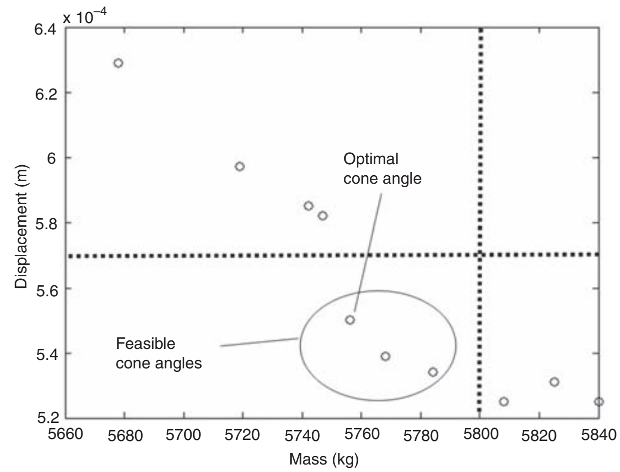

Figure 7. Maximum displacement *vs* machinery mass.

space by combining an engineering process supporting creation of models with analysis of models within the same control space for a specific product architecture. The following features differentiate the proposed MM approach from most applications of 'traditional' KBE systems: (1) The MM control logic is simple and defined independent of each implementation based on the information flow. The implementation independent control logic allows engineering designers and non-programming experts to stay focused on the use and overall effect of using the system. Further, the introduction of new features and capabilities can easily be identified and the system becomes less dependent on the features of the software used. (2) The MM allow access to various high-level features in the CAD system, such as volume calculations and operations pre-defined in the CAD system, which typically required programming previously. Several CAD/PLM vendors have introduced declarative languages to enable generative modeling within their system, and despite some inconsistencies between the declarative, demand-driven nature of the programming technique and the procedural, parametric techniques used in the core of the CAD/PLM tools, it is easier to create product models that align with the CAD modeling standards applied within companies. Less programming is required to combine high-level functions and still align the product structure with the CAD model preferred for continuing detailed modeling beyond the optimization activities. (3) The simple MM logic simplifies the integration of an optimization approach, since the architecture and control view of the MM is kept minimal and simplistic.

5.1 Future Work

The KBE-based MM approach has been developed with the objective to be utilized for decomposition-based MDO. Specifically, we will utilize the MM framework to manage the analysis models required for conducting analytical target cascading (ATC) optimization studies in the further product development. ATC is a rigorous, mathematical systems engineering methodology developed to support decomposition-based design optimization activities [26]. An optimization problem is formulated and solved for each element of a decomposed system to minimize deviations of local responses from propagated targets. In this manner, ATC quantifies and takes system interactions into account while determining component design specifications to satisfy system-level design targets. The iterative solution of these sub-problems using appropriate coordination strategies yields designs that provide system-level optimality while ensuring system integration. The ATC methodology has convergence properties [27] and has been applied, enhanced, and extended continuously and broadly in the recent years [28–30]. The MM approach will be used to coordinate the analysis models required for the ATC process by generating models of appropriate abstraction and fidelity for the various levels of the system decomposition.

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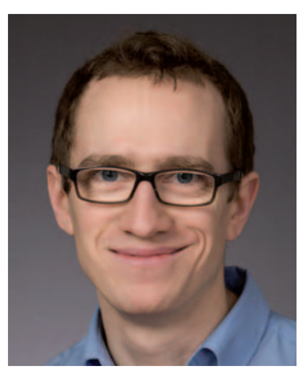

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