

A Preprocessor for Parametric Composite Rotor Blade Cross-Sections

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Structural helicopter rotor blade optimization comprises classical aeroelastic problems, where the aerodynamic behavior, the structural elasticity and vibrational dynamics have to be studied simultaneously. Since the dynamic and modal behavior is strongly related to the structural properties of the rotor blades, adjusting these properties is essential for an effective optimization. Nevertheless, identifying constraints based on elemental matrices to keep the solution within feasible boundaries is often a protracted and iterative task. In this paper a structural preprocessor for parametric analysis and design of composite beam cross-section is presented. The herein presented definition of the rotor blade topology is deliberately associated to the production of composite rotor blades. Thus, manufacturability is inherent from the geometric layup definition. Using orthogonal projection with corner-style differentiation the cross-section is discretized and processed by the Variational Asymptotic Beam Sectional Analysis (VABS) afterwards. The approach is successfully demonstrated with generic UH-60A composite rotor blade cross-sections.

Nomenclature

m_{00}	Mass per Unit Length
X_{m2}	Mass Center Location
EA	Axial Stiffness
EI_2	Bending Stiffness about y Axis
EI_3	Bending Stiffness about z Axis
GJ	Torsional Stiffness
CBM	Composite Beam Model
LE	Leading Edge
TE	Trailing Edge
VABS	Variational Asymptotic Beam Sectional Analysis

Introduction

The large number of constraints and design drivers from various disciplines makes the helicopter rotor blade development process difficult, time consuming and costly.

The entire design process represents a classical aeroelastic problem, where the aerodynamic behavior, the structural elasticity and vibrational dynamics have to be studied simultaneously. The behavior can therefore not be examined with separate analysis of the different disciplines [1].

The integration of all the appropriate disciplines in the design process implies not only limitations on the design from various disciplines, but also defining and accounting for interactions so that the disciplines influence design decisions simultaneously rather than sequentially [2].

Historically, the design and development of improved or entirely new rotor blades is conducted by departments in a company that maintain their separate simulation codes for performing their specific tasks. The aerodynamics department is responsible for performance calculations, aero-acoustics, rotor-wake interaction, unsteady airload prediction and computational fluid dynamics while the dynamics department focuses on rotor vibratory loads, stability and aeroelastic models [1]. The structural department determines the elastic properties as well as strength and fatigue characteristics. A Blade and Rotor Design Department often bundles the different aspects while considering materials, manufacturability, maintainability and safety requirements. [1]

This modular approach narrows the scope of solutions, because each department focuses on individual objectives satisfied by individual design parameters. Mutual interactions can only be covered by numerous iterations.

In contrast to that, a multidisciplinary approach offers a more systematic development process that is able to design a better helicopter rotor [2]. Because of the impact the rotor behavior has on the overall performance of the helicopter and on customer noticeable vibratory characteristics, rotor aeroelastic effects should be considered in the earliest stages of the design process [3].

In the last 25 years, researchers have repeatedly stated the need for a design methodology and optimization frame-

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work that combines computational efficiency of a beam description in aeromechanic analysis with a rotor blade structural model that is capable at describing realistic composite rotor blade cross-sections with respect to the structural properties, applied load, stress and strain distributions as well as design constraints [4–6]. Our multidisciplinary rotor blade design framework is named SONATA (Structural Optimization And Aeroelastic Analysis) and is illustrated in the following figure 1. Like most environments it comprises of three main components that are wrapped into an optimization framework.

As a first component, the current state of the art involves an aeromechanical analysis of rotorcraft blades which includes flexible multibody dynamics, nonlinear finite elements and various rotorcraft aerodynamic models. They are often referred to as Comprehensive Analysis. Examples are the widely used Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics II (CAMRAD II) [9] and the software Dymore [10] beyond several others. Both of these codes are presently in use in the rotorcraft industry, academic institutions and government laboratories. The quality of the predictions have been documented in numerous publications. In our SONATA environment Dymore was chosen as aeromechanic tool for both a dynamic analysis in the time domain as well a modal analysis within the frequency domain.

In this context classical 1D-beam elements are used to describe the rotor blade due to the much simpler mathematical formulation and reduced computational effort compared to a full three-dimensional finite element model of the composite rotor blade [11]. Typically, this approach decouples the realistic composite blade definition and the manufacturability constraints from the aeromechanic analysis and the predesign of structural blade properties. That way, problems in the blade design cannot be discovered until later in the process where changes are costly and time consuming [12].

Although the three-dimensional finite element method is the most accurate approach to model realistic rotor blades, it is still not appropriate for the use in rotor blade predesign [11, 13]. The slender characteristic of rotor blades allows the simplification to treat them as one-dimensional body [14]. Cesnik and Hodges [15] formulated the Variational Asymptotic Beam Sectional Analysis (VABS) to accurately represent the behavior that is associated with the reduction of two-dimensions. In other words, this method splits the three-dimensional elastic problem into a two-dimensional linear cross-section analysis and a one-dimensional nonlinear beam analysis, which is able to consider initially twisted and curved, anisotropic, non-homogeneous materials to model general composite cross-sectional geometries [13, 15]. VABS is the second component of our environment.

In the last 20 years, VABS and its variations have become a popular tool in rotor blade predesign and multidisciplinary rotor design optimization and their accuracy

and efficiency has been validated in numerous publications [3, 15, 16]. While a geometric definition of a rotor blade with CAD tools is simple, the transfer to a meshed cross-sectional representation may prohibit automated design optimization. Consequently, most researches have developed individual parametric mesh generators for the cross-sectional analysis, that reduces their structural model to few design variables in the process. Such a preprocessor for parametric composite rotor blade cross-sections (referred as *SONATA-CBM*) with its discretization strategy is presented in this paper. It is the third component of the SONATA environment. A short review of a selection of individual parametric mesh generators is given in the section below:

Li et al. [13] presented a parametric mesh generator that can efficiently model and mesh a precise cross-sectional layout in relation to the selected design variables. Parameters chosen for the optimization are ply thickness and fiber orientation, spar location and orientation etc.. Its unique feature is that the optimization model is improved by structural and manufacturability constraints.

Lim et. al. [6] have used the front and rear shear web position of the composite cross section as well as the number of plies and fiber orientation as variables in their design optimization. The rotor performance and vibration analysis was carried out by CAMRAD II, while they used VABS for a detailed cross-sectional analysis with regard to multiple constraints such as structural integrity, location of shear center and discrete ply orientation. They used a response surface method and genetic algorithm in a MATLAB environment as optimization procedure.

Rohl et al. [3] presented a cross section mesh generator preprocessor IXGEN that uses a graphical modeling interface to define the cross-sectional composite layup of a rotor blade. Subsequently they use the University of Michigan version of VABS to feed the cross sectional mass and stiffness properties into a comprehensive rotorcraft analysis code (RCAS). IXGEN was developed with the support of the US ARMY Research, Development and Engineering Command (AMRDEC). It uses OpenCascade, an open source CAD geometry kernel to generate the 3D rotor blade geometry and the 2D cross-sectional meshes. This provides the functionality to export the geometry to 3D CAD software in standardized formats. Again each cross-section is specifying features such as spar webs, spar caps, wrap layers, etc. that can be used as design variables during the optimization.

Kumar and Cesnik [17, 18] applied the described optimization framework for the aeroelastic analysis and design of an active twist rotor and showed that by using their multidisciplinary design optimization method, the active twist 4/rev actuator authority can be maximized.

Silva [19] stated the plan to integrate IXGEN into an Open-MDAO Rotorcraft Optimization Framework called RCO-TOLLS which currently contains a Python interface for the NASA Design and Analysis of Rotorcraft (NDARC) vehicle sizing tool and CAMRAD II [20].

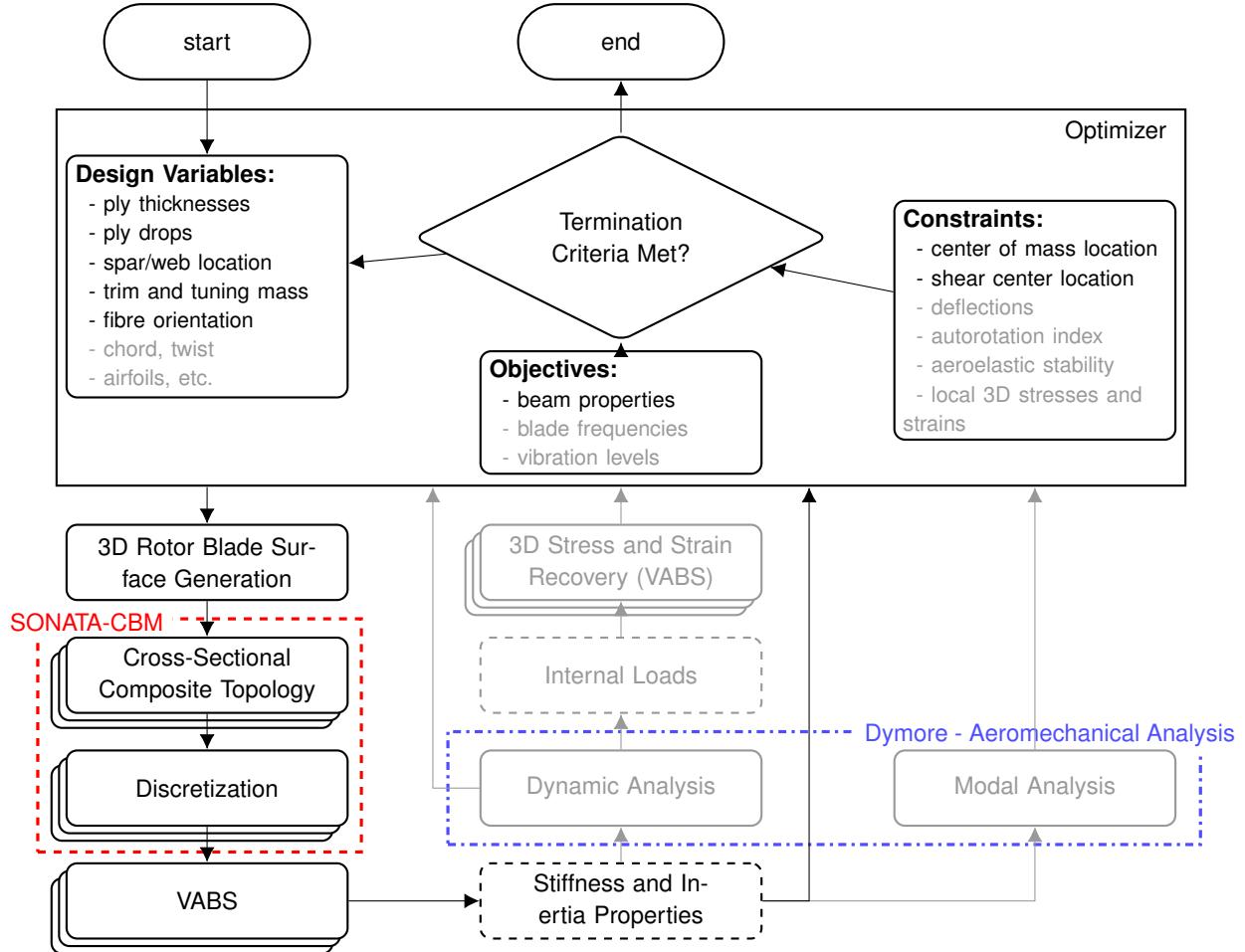


Fig. 1: SONATA: Multidisciplinary Rotor Blade Design Environment for Structural Optimization and Aeroelastic Analysis embedded in *OpenMDAO* [7,8]. The grayed out paths are in the outlook of the multidisciplinary optimization and not part of this paper.

Glaz et. al. [21, 22] have studied rotor blade structural surrogate-based optimization for vibration reduction in the low-speed regime and at high advance ratios. The vector of design variables describes a simplified structural model of a cross-section with thickness, nonstructural mass at several span-wise locations. They showed that a successful reduction of vibrations is possible with a optimized structural design, even the source of high vibrations are significantly different at both flight states. Blade vortex interaction (BVI) at low-speeds and dynamic stall at fast forward speeds.

Additionally, Yu [23] and his coworkers have developed various VABS interfaces for commercially available FEM packages such as ANSYS and ABAQUS and just recently released an open-source preprocessor for VABS called Pre-VABS [24] that uses Gmsh for mesh and visualization capabilities.

While most researchers assume a specific predefined topology of the cross-section, some apply general topology optimization to the problem. Such a method can be interesting for a conceptual predesign of rotor blades, because almost any shape can be generated [25]. However, while

computational loads are significant, Fanjoy and Crossley [25] highlight the possibility to search and locate unconventional design solutions that can be used as starting point for further optimization. Blasques [26] studied a multi-material topology optimization of composite beams with eigenfrequency constraints. The optimization is performed within a 2D multi-material topology optimization framework. The design variables represent the volume fractions of different candidate materials at each point in the cross section [26]. Drawbacks are the large necessary computational resources and the large effort to implement structural and manufacturing constraints.

Last but not least, the tree components are managed by an environment where design variables and objectives can be defined, constraints to be applied and solvers to be launched. The SONATA framework uses *OpenMDAO* [7, 8, 27], an open-source computing platform for system analysis and multidisciplinary optimization, written in Python. It allows the user to break down the structure of complex optimization tasks into a hierachic manner while managing the numerical methods.

A Python-based wrapper for Dymore has been devel-

oped to integrate the dynamic and modal analysis into the OpenMDAO-driven optimizations. Consequently *SONATA-CBM* has been written in Python using the Python wrapper for the CAD-Kernel Opencascade pythonOCC [28].

Methodology

SONATA-CBM's composite topology generation originates from an arbitrary closed curve that can be obtained from various input formats that range from airfoil coordinate tables over a 3D CAD rotor blade surface definition (.step or .iges) with radial station to a parameterized rotor blade with twist, planform, airfoil and chord-line distribution. In the case of the latter two, the 3D surface is intersected at a certain radial station to obtain once again a two-dimensional outer boundary of the cross-section. Figure 2 shows the resulting parameterized 3D surface of the UH-60A rotor blade with a cross-section topology at radial station $R = 2000\text{mm}$.

While the following methodology is shown with the example of the UH-60A rotor-blade, it should be noted that this procedure can be applied to any closed curve cross-section, and therefore be also used to model rotor blade root sections or any other composite beam cross-sections.

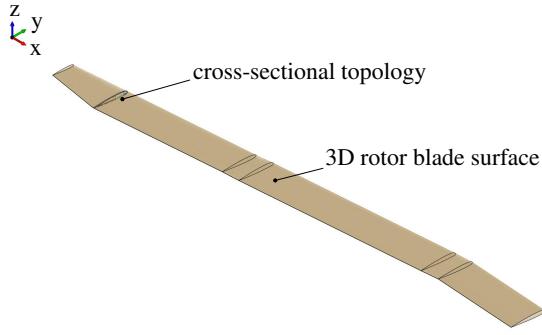


Fig. 2: Parameterized 3D surface of the UH-60A rotor blade created with twist, planform, airfoil and chord-line information from Davis [29]

Topology Generation

The process behind the composite topology generation is derived from the manufacturing process, where the layers are placed on top of each other in negative molds in a consecutive manner to avoid complex constraints in the optimization and to keep the solution within proper bounds. Each layer has an assigned material with start and end coordinates, a thickness and fiber orientation (see table 1). Every parameter or groups of them can serve as design variable in the later optimization. After the layup process on top of the outer boundary curve is completed, webs are introduced and subsequently new closed curved geometries are generated where the layup procedure is repeated. Cavities can be filled with core materials and additional trim

masses can be inserted.

At first the outer boundary curve, represented as counter-clockwise sets of consecutive B-splines, is defined in curve coordinates s between zero and one. The origin is typically located at the trailing edge (TE). The curve coordinate system propagates through the layers with an interval tree structure. It allows to efficiently find the intervals/layers that overlap and locate the corresponding coordinate for each layer. Subsequently, each layer is generated by the following consecutive steps.

1. Determine the relevant set of underlying B-Splines between *start* and *end* coordinate of the layer using an interval tree data structure.
2. Discretize the set of B-Splines and perform an parallel offset to return an approximate representation of all points with a given thickness of each layer.
3. Generate a new set of B-Splines by interpolation and add smooth layer cutoffs to connect the lower and upper set of B-Splines if necessary.

In table 1 the layup definition of the cross-section, illustrated in figure 3, is displayed. Note that the shown genetic composite cross-section of the UH-60A serves as demonstration of the modeling capabilities of the framework in this paper.

start	end	thickness [mm]	orientation [$^{\circ}$]	material ID	name
Segment 0					
0.44	0.56	0.82	0	7	Erosion Strip
0.00	1.00	0.25	0	8	Overwrap Ply 1
0.00	1.00	0.25	± 45	8	Overwrap Ply 2
0.00	1.00	0.25	± 45	8	Overwrap Ply 3
0.00	1.00	0.25	0	8	Overwrap Ply 4
0.45	0.55	1.00	0	2	Spar 1
:	:	:	:	:	:
0.48	0.52	1.00	0	2	Spar 7
Segment 1 (Core Material 3)					
0.00	1.00	0.80	45	2	Spar 8
0.00	1.00	0.80	-45	2	Spar 9
Segment 2					
0.00	1.00	1.35	0	9	Spar Cap Ply 1
0.00	1.00	1.35	45	9	Spar Cap Ply 2
0.00	1.00	1.45	-45	9	Spar Cap Ply 3
0.00	1.00	0.50	90	9	Spar Cap Ply 4
Segment 3 (Core Material 11)					
0.96	0.04	0.8	45	8	TE Filler

Table 1: Layup definition of figure 3

The first set of layers are grouped into Segment 0. The first layer that is generated is a steel erosion protection strip

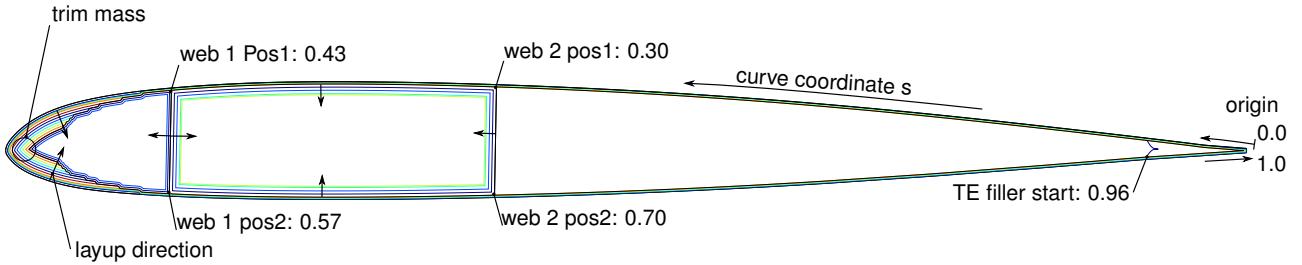


Fig. 3: Topology definition of a generic composite UH-60A rotor blade cross section.

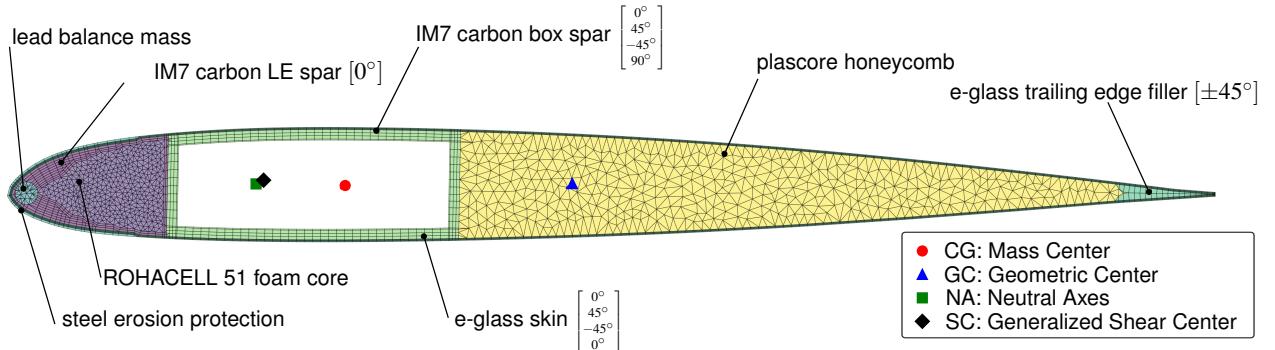


Fig. 4: SONATA-CBM discretization of a generic composite UH-60A rotor blade cross-section in reference to [3] to illustrate the modeling capabilities.

that ranges from coordinate 0.44 to 0.56 with a thickness of 0.82mm. Because of the isotropic material used, the orientation can be neglected for this layer. The material ID represents a reference index of an associated material database. The next 4 layers define the skin of the rotor blade placed in both 0° and $\pm 45^\circ$ orientation on top of each other. The layers Spar 1 to Spar 7 are unidirectional carbon fiber composite layers that generate a C type spar with ply drops in the leading edge region of the cross-section. Once the first set of layers (Segment 0) has been created, webs are introduced to the structure. They are defined as straight line between two positions. In this example the first web ranges from coordinate 0.43 to 0.57 while the second is placed behind from 0.30 to 0.70.

The three newly generated closed curved geometries are used to repeat the layup procedure. During the manufacturing process this translates to a process of wrapping plies around a core. A core material is assigned to Segment 1 and 3 that fills up the remaining cavity. Segment 2 consists of four carbon fiber layers of different orientation from 0 to 1 to generate a hollow box spar.

After the layup is defined a trim mass can be placed on top of the existing layers and will be integrated in the structure during the discretization.

Discretization

The discretization follows the topology generation procedure, yet in a reversed direction with respect to the layup definition, starting from the innermost layers and moving outwards. Each layer is meshed by an orthogonal projection with corner style differentiation. Figure 4 shows the

final result of the described procedure.

Each layer can be described by two sets of B-splines, the inner $a_{bsplines}$ and outer $b_{bsplines}$. The nodes placed on them are called accordingly a_{nodes} and b_{nodes} . The following procedure is applied to each layer, starting at the innermost, and moving outwards.

1. Determine existing a_{nodes} based on the intervaltree structure of the layup. If sections on the $a_{bsplines}$ are found with no preexisting nodes, distribute new nodes equidistantly.
2. Create an orthogonal projection of each a_{node} onto the set of $b_{bsplines}$. If two or more projections are found determine the angle α and the number of potential $b_{bsplines}$ corners between them.
3. Based on a critical angle α_{crit} and the number of exterior corners determine the corner style and as a consequence the meshing procedure. In figure 5-7 the first 6 different corner styles are shown.
4. After all nodes are placed on both sets of B-splines, they are connected to form cells with associated material and ply angles.
5. In subsequent steps sharp cells, large aspect-ratio cells and cell angles are modified to improve mesh quality.

As soon as every layer of the segment is meshed, the remaining cavities are triangulated using Shewchuk [30] algorithm with an area constraint. To avoid hanging nodes

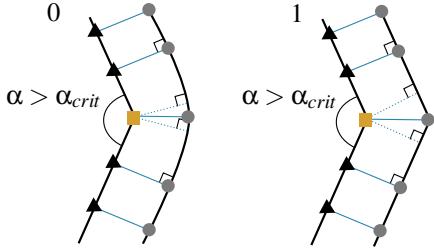


Fig. 5: Corner-style 0: no exterior corner on b_{bsplines} and $\alpha > \alpha_{\text{crit}}$; Corner-style 1: one exterior corner on b_{bsplines} and $\alpha > \alpha_{\text{crit}}$

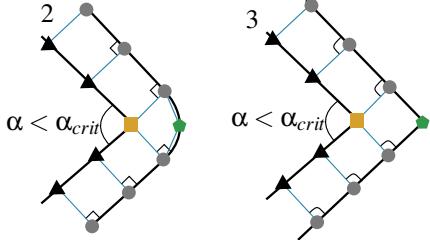


Fig. 6: Corner-style 2: no exterior corner on b_{bsplines} and $\alpha < \alpha_{\text{crit}}$; Corner-style 3: one exterior corner on b_{bsplines} and $\alpha < \alpha_{\text{crit}}$

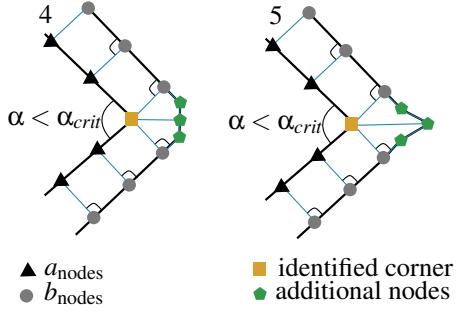


Fig. 7: Corner-style 4: two exterior corners on b_{bsplines} and $\alpha < \alpha_{\text{crit}}$; Corner-style 5: three exterior corners on b_{bsplines} and $\alpha < \alpha_{\text{crit}}$

between two neighboring segments, the cells are consolidated on web interfaces.

In a final step, the previously defined trim mass is integrated into the described mesh by mapping existing nodes onto the trim mass contour. The corresponding algorithm is schematically illustrated in Figure 8 and described below:

1. Determine the number of inner nodes of the intersected cells.
2. Move the inner nodes of the cells marked 1 along the cell edge with shortest distance to the intersecting curve.
3. Move the remaining inner nodes of the cells marked 2 along the cell edge with shortest distance to the intersecting curve.
4. Move the outer node of the cells marked 3 along the edge direction onto the intersecting curve.
5. Delete cells marked 3 and 4.

6. Use the boundary nodes as starting point for the inner triangulation.

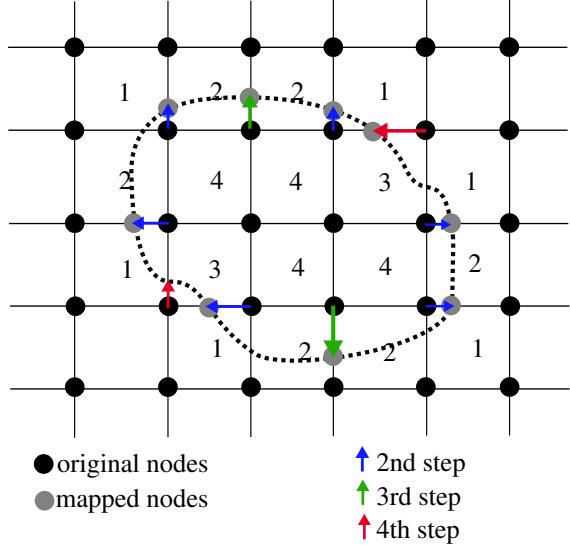


Fig. 8: Mapping algorithm to integrate curves into an existing mesh

The final result is displayed in the magnified cutout of the leading edge region in figure 9.

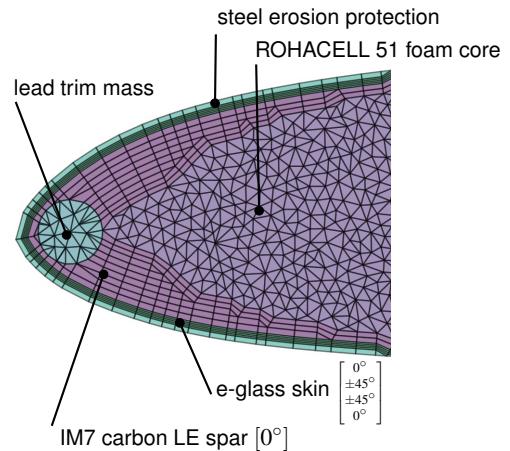


Fig. 9: Leading edge region of figure 4 showing the ply-drops of the C-Spar and the integration of the trim mass into the existing mesh.

Finally, the VABS input files are generated from the mesh together with the material information from an associated database. To verify the resulting stiffness properties, simple benchmark testcases for isotropic and anisotropic box-beam cross-sections have been set up and compared to results from [31]. Moreover, the rotor blades of the institute's high altitude synchropter UAV (AREA) [32,33] have been reengineered with SONATA-CBM and compared to experimental results from Suesse [34].

Application: UH-60A Demonstration

In the last section the SONATA-CBM preprocessor was presented, while at the same time, a generic composite cross-section was introduced serving as an example. This section is a demonstration of the modeling capabilities within the optimization framework. The cross-section of figure 4 is used as initial starting condition for an optimization strategy with the objective to reach the original UH-60A beam properties from [35] and [29] at two radial stations.

Design variables chosen for this demonstration are illustrated in table 2. The thicknesses of the four sparcap

design variable	start	lower	upper	result	unit
ρ_{mat3}	0.05	19.25	0.05	1.38	g/cm^3
$t_{sparcap1}$	1.35	0.35	2.7	1.49	mm
$t_{sparcap2}$	1.35	0.35	2.7	1.38	mm
$t_{sparcap3}$	1.45	0.35	2.7	1.48	mm
$t_{sparcap4}$	0.45	0.35	2.7	0.53	mm
s_{w1}	0.43	0.35	0.43	0.42	-
s_{w2}	0.3	0.2	0.32	0.29	-
s_{spar2}	0.46	0.445	0.476	0.45	-

Table 2: Design variables and results for $R=2000\text{mm}$

layers enables an adjustment of the proportions of fiber orientations in the boxspar. The density of core material 3 (ρ_{mat3}) was chosen to allow the optimizer to modify the mass and the location of the center of gravity. The lower boundary represents a foam core while the upper boundary represents solid tungsten. Additionally the chordwise location of both webs are design variables s_{w1} and s_{w2} . To demonstrate the possibility to modify layers in a c-spar ply-drop, the start coordinate of second spar layer s_{spar2} is added to the set of design variables. The end coordinates of web-definitions and spar layer depend on the start coordinate to ensure a certain symmetry in the topology.

Two radial stations ($R = 2000\text{mm}$ and $R = 7500\text{mm}$) were selected for the demonstration. Both cross-sections use the same initial configuration, set of design-variables and boundaries.

The original stiffness and inertial properties of [29] are used to set up an optimization. In figure 12 the beam properties of the cross-sections are shown in contrast to the original UH-60A titanium box spar rotor blade.

The objective is defined as root mean square deviation of mass per unit span m_{00} , center of mass location X_{m2} , axial stiffness EA , flatwise and edgewise bending stiffness EI_2 and EI_3 as well as the torsional stiffness GJ between the proposed new rotor-blade and the original. The scalar objective is minimized using Sequential Least SQuares Programming (SLSQP). The optimization ran for approximately 10-15 Minutes using 17-20 function evaluations.

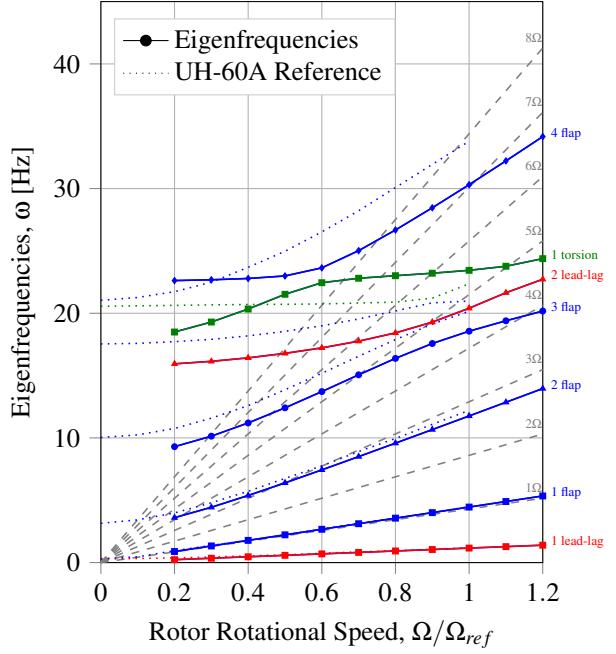


Fig. 10: Fan-Plot of the new rotor-blades compared to the UH-60A Fan-Plot from Bowen-Davies [36].

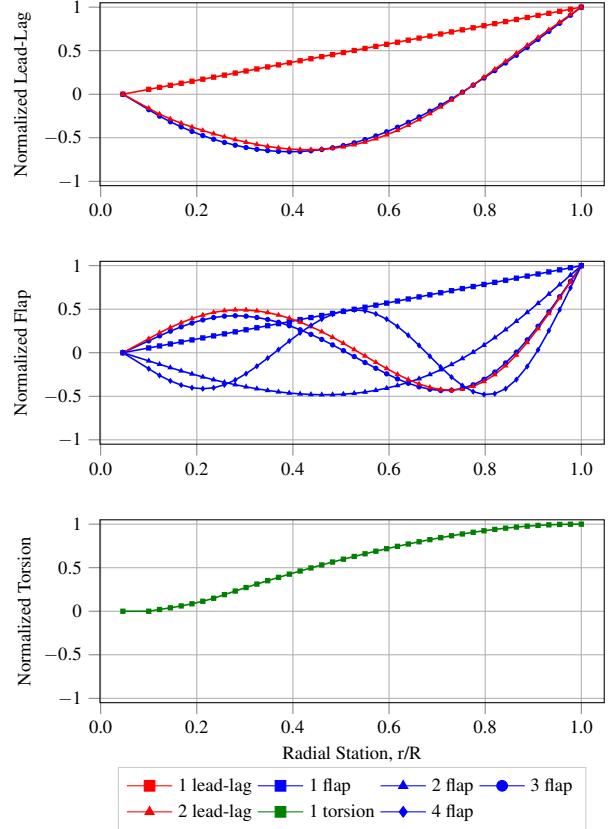


Fig. 11: Corresponding rotor-blade modes to the Fan-Plot from figure 10

The optimized design has the following characteristics: The density ρ_{mat3} was increased at both radial stations to increase mass per unit length and move the center of gravity closer to the leading edge. The lead-lag stiffness and

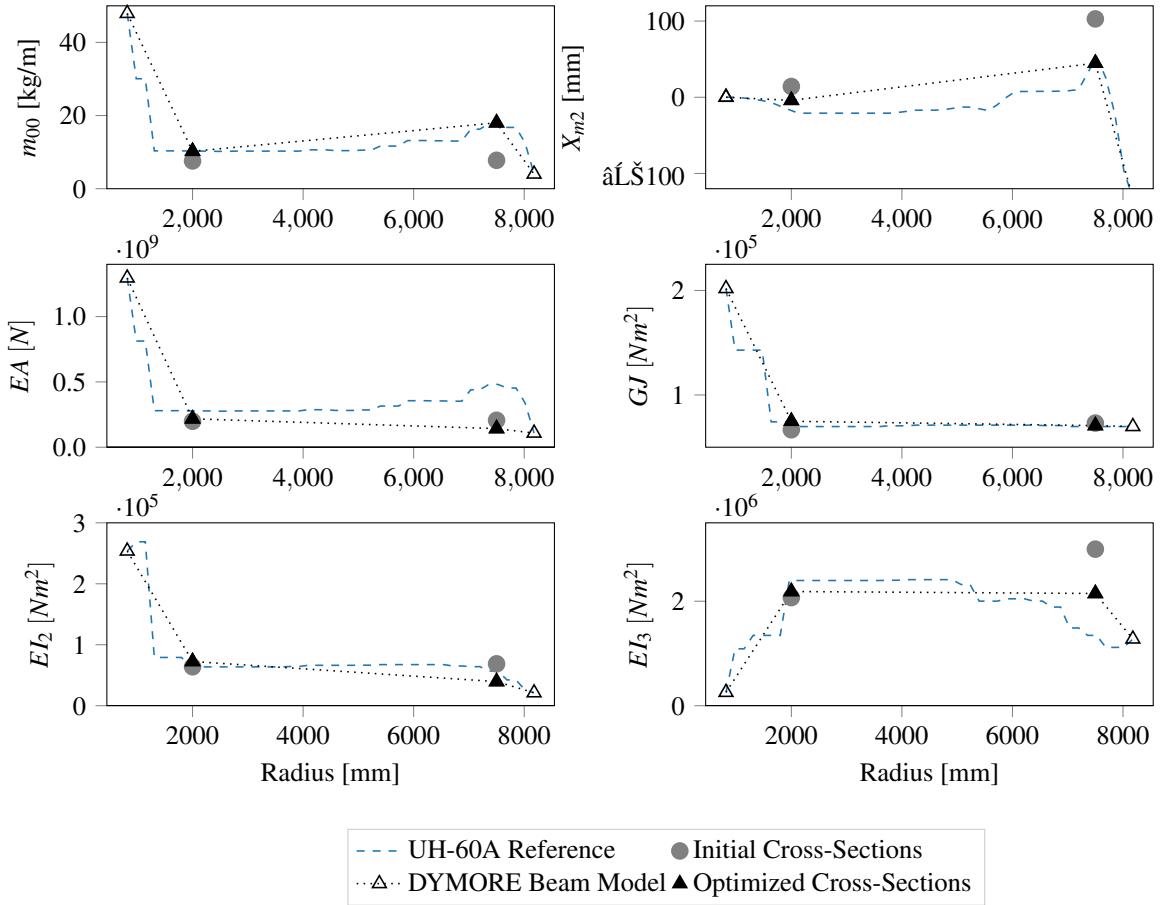


Fig. 12: UH-60A rotor blade beam properties in comparison to the generic composite cross-section from figure 4.

the axial stiffness are conflicting goals that the optimizer didn't solve.

For the sake of completeness the resulting beam properties are used for a modal analysis with Dymore. The Fan-Plot with the rotor-eigenfrequencies and the corresponding eigenmodes at nominal rotor speed are shown in figure 10 and 11. The 3rd flap and 2nd lead-lag mode show strong coupling at nominal rotor speed. In addition to that, large differences compared to the UH-60A Fan-Plot from Bowen-Davies [36] are visible.

We can conclude that the number of design variables and boundaries were restricted in a too conservative manner so that the method has not made full use of its potential. Moreover, a gradient based method may not be the best approach to explore all feasible solutions in the design space. This is shown by the fact that the optimizer converged at solutions close to the initial parameters and did not reduce the overall deviation to zero (11% RMSE at R=2000mm, 38%RMSE at R=7500mm). However, the application of the presented preprocessor SONATA-CBM in a small optimization example is solely to demonstrate the capability of tool for the use in larger optimization tasks.

Conclusion and Outlook

An efficient parametric design methodology for composite beam cross-sections has been developed that allows an integration into a multidisciplinary preliminary rotor blade design framework. The structural preprocessor SONATA-CBM's definition of topology deliberately uses the production process of composite rotor blades. Thus manufacturing constraints are immediately considered. The Preprocessor is written in Python to use in an OpenMDAO framework, in which it is currently used together with VABS and a python wrapper for the finite element based multibody dynamics code Dymore.

In the future, it will be used for comprehensive multidisciplinary rotorcraft optimization tasks, where the entire rotor-system can be optimized with respect to objectives such as eigenfrequencies, vibratory loads, aeroelastic stability and structural integrity.

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