Geometry Model and Approach for Future Blisk LCA

Kilian Fricke, Sascha Gierlings, Philipp Ganser, Tommy Venek, Thomas Bergs
Fraunhofer-Gesellschaft, Institute for Production Technology IPT, Steinbachstr. 17, 52074 Aachen, Germany

Website: www.ipt.fraunhofer.de
Email: kilian.fricke@ipt.fraunhofer.de

Abstract. Air traffic is expected to double over the next 20 years and Flightpath 2050 targets to a 70 % reduction of CO2 and a 90 % reduction of NOx. Optimization of future aircraft engines often is dominantly driven by a focus on the reduction of fuel burn and emissions during operation. To identify additional environmental improvement potential a full Life Cycle Analysis (LCA) shall be aspired also including Materials, Processes and Resources, Manufacture and Production, Lifetime Services as well as Reuse, End-of-Life and Recycling. Core engine components, for example integral rotors, are comprised of Titanium- or Nickel-alloys and require complex manufacturing processes.

A geometry design model of a compressor blisk is introduced which is employed as basis for a future LCA approach focusing on materials, processes and resources as well as manufacture and production. The model is a carrier for challenging manufacturing features such as large blade twist, high aspect ratio and small blade gaps. In addition to the geometry model, a first set of multiple technology scenarios and their process chains will be introduced which will serve as base for a future LCA.

1. Introduction

Global air traffic has roughly doubled every fifteen to twenty years and it is estimated that this trend will continue in the near future, albeit with some adjustments due to the Covid-19 impact [1]. The EU initiatives Flightpath 2050 and Clean Sky are currently the central drivers of the technology development in the aviation sector. The objectives of Flightpath 2050 relative to a reference engine from the year 2000 are [2]: 75% reduction of CO2 emissions per passenger kilometer, 90% reduction of NOx emissions per passenger kilometer and 65% reduction of noise emissions.

In addition to the operation phase, also resource efficient manufacturing is relevant for the overall ecological assessment. The construction of aero engine components is of particular interest as the engine design has a large influence along the entire lifecycle. Integrially manufactured compressor rotors or blisks (blade integrated disks) represent one of the most challenging components within aero engines from a manufacturing point of view [3]. Complex geometries, small tolerances and highly resistant materials such as Titanium- and Nickel-alloys require complex manufacturing process chains. A study has been set up for an alternative material choices for blisks.

This document describes the blisk model which shall be used as common research model for the analysis and the manufacturing scenarios to be evaluated as representative for advanced engine manufacturing technologies with regard to economic and ecologic aspects for future life-cycle-assessments. The design of the blisk model was discussed and adjusted with partners from the industry within the Clean Sky 2 Engine ITD (Innovative Technology Demonstrator).

2. Design of Blisk Model

The blisk model represents a typical High Pressure Compressor (HPC) rotor featuring the complexity of an ambitious aero-engine design. The model primarily has been developed to serve as carrier for challenging design features driving the limits of manufacturing technology with regard to expected future blisk applications. Aerodynamic and structural performance of the model have not been driven to an overall optimum but its geometric design features are expected to meet the most relevant challenges for the manufacturing of blisk designs for future engine applications. Thus, the model represents a proper base of analysis for the evaluation of advanced manufacturing technologies for future blisk manufacturing. The blisk model is a full 3D CAD Model allowing to derive the required information for manufacturing (Figure 1).
From a manufacturing perspective, integral compressor-rotors (“blisks”) are especially interesting as the manufacturing complexity and efforts per part are rather high compared to parts in other engine subsystems. The main reasons for this are:

- Smaller core sizes [4]
- The integral design of the airfoils and the hub section in combination with the relatively small part size requiring the machining from a single piece of material
- The complexity of the geometry for the airfoils (due to long, filigree airfoils that exhibit high twists and varying cross-section profiles)
- The material selection for HPC parts is limited to a small bandwidth of titanium or nickel-based super-alloys that are difficult to machine and hence are very cost and resource intensive.

![Figure 1: Illustration of the blisk CAD-model and its basic geometries](image)

In contrast to engines of the 4th Generation (e.g. CFM56-B or V2500 in the ~ 30k lbf thrust range) where HPC rotors consist of single blades mounted to a hub, state-of-the-art 5th Generation engines (entry into service 2010’s; such as the CFM Leap or the PW1100G in the same performance class) feature integral compressor designs due to weight and performance reasons. Aiming at Next Generation (EIS early 2030’s) engine designs, HPC rotors will remain integral parts. [5] However, due to an increase of the engine overall pressure ratio (OPR) being a key performance driver for the overall efficiency, the HPC section will be operated at higher pressures and temperatures. This leads to smaller core engine sizes and a change towards even higher temperature stable materials – especially for the rear stages in the compressor section. The focused design model represents a blisk that is approx. a Stage 2 to 4 of a 9 to 12 stage HPC module (compare Figure 2 showing the location in the engine).

In order to generate higher pressures up to OPR’s of approx. 60 by subsystems operating in the same range in terms of weight and installation space, the design of the part will radically change.
The main changes compared to state-of-the-art compressor-rotor designs express in:

- A more complex 3D shaped geometry of the airfoils with higher twists in order to enhance the efficiency of the part compared to state-of-the-art components exhibiting ruled surfaces and higher chord length),
- Higher blade densities and therefore smaller spacing between the airfoils (complicating the engagement of tool and measurement equipment),
- Significantly smaller geometric tolerances across the entire part (as gaps to interfaces and the aerodynamic performance gets more critical for relatively smaller parts).

![Figure 2: Subsystems of modern turbofan engine with localization of part in focus](image)

2.1. Design features and composition of the blisk model

The blisk model intends to represent an extremely challenging manufacturing scenario for an integral HPC rotor. However, a major problem for the discussion of manufacturing scenarios is, that component models do not yet exist in early design stages. This is in the nature of the engine design process starting with 1D or 2D thermodynamic and aerodynamic concepts until the very first performance investigations of rudimentary 3D airfoils can be made in a simulation environment – still being far from component models taking into account the rotor as it is in the later engine. For that reason, the blisk model has been derived on the basis of performance-relevant data, i.e. uses thermodynamic data in order to estimate the relevant boundary conditions for aerodynamic features such as

- The basic geometry, i.e. actual part size from hub to tip, blade height, chord length and total number of blades,
- The vectors for incident and escape flow over the airfoil height resulting in the twist of the blade features,
- The varying cross section profiles from the fillet radius to the tip of the blade
- The principal elliptical design of the leading and trailing edge [6]
- Aerodynamic features such as forward or backwards directed sweeps
- The design of the fillet radius at the interface between the airfoil and the platform of the hub

By taking into account actual performance data sets, it is ensured that the blisk model is not a mere manufacturing worst-case scenario without any relevance, but is sufficiently close to realistic geometric design envelopes for engine HPC rotors. For the hub section, however, structure mechanical considerations are not included into the design model. Here, the basic geometry was designed as HPC compressor parts with its typical features and that are challenging from a manufacturing perspective.

2.2. Basic geometries

An overview of the basic geometry is shown in Figure 3. The outer diameter of the part was set to 440 mm. The hub diameter is set to 240 mm resulting in an airfoil height of 100 mm. With a chord length of \(l = 45\) mm the blisk follows the trend of higher airfoil aspect ratios which go in line with
additional compressor stages in the subsystem. The number of blades for the part in focus is \( N = 30 \), i.e. the distance-to-chord-ratio amounts to 0.66.

**Figure 3: Basic geometric data of HPC blisk (blisk model)**

As indicated in Figure 3, the compressor stage was analytically calculated to an efficiency of approx. 90% without any CFD optimizations done. The analytic calculation in a first step were done for the cross section profile at the half blade height (Figure 4).

**Airfoil Cross-Section**

**Aerodynamic Data:**

- Flow Coeff.: \( \varphi = 0.5 = \frac{C_d}{\Delta h} \)
- Work Coeff.: \( \psi = 0.7 = \frac{h_l}{\frac{h_l + \Delta h_{tr}}{w_{in}^2/2}} \)
- Enthalpy Coeff.: \( \rho = 0.55 = \frac{h_{in}}{\Delta h_{tr} + \Delta h_{tr}} \)

**Boundary Conditions**

\( \eta (\text{analytical efficiency}) \approx 90\% \)

**Aerodynamic Conditions**

- Height-to-Chord-Ratio: \( \frac{h}{l} = 2.22 \)
- Blade-Distance-to-Chord: \( \frac{r}{l} = 0.66 \)

**Annular Geometry**

- Blade Height: \( h = 100 \text{ mm} \)
- Hub Radius: \( r_n = 120 \text{ mm} \)
- Tip Radius: \( r_g = 220 \text{ mm} \)
- Hub-to-Tip-Ratio: \( \frac{r_n}{r_g} = 0.545 \)

2.3. **Blade geometry**

The calculation of the radial distribution of the incident and escape flow vectors are done by solving the Navier-Stokes-Equation simplified using the following assumptions:

- Circumferential symmetry of the part,
- Stationary flow conditions,
- Flow lines are assumed on a cylindrical surface,
- Isentropic change of state, and
- Free vortex as a further boundary condition. [8]

In a next step, the total blade twist can be determined based on the angular distribution over the airfoil height (i.e. by the difference of the incident and escape flow angle in the root and at the tip of the blade). The twist angle is the first parameter influencing the blisk model blade feature. Together with the stacking axis of the blade, the skeleton line for the airfoil is designed. The next parameter going into the blade feature is the airfoil cross section, i.e. the profile form. According to the state-of-the-art,
compressor profiles are commonly designed on the basis of profiles from the NACA series (such as NACA 65), double circular arc (DCA) or controlled diffusion airfoil (CDA), compare Figure 5, bottom left-hand side. The blade of the blisk model was designed as advanced high turning compressor airfoils for low Reynolds-Number conditions using DCA profiles with a location of maximum thickness at ~ 0.5 chord length and location of maximum camber at ~ 0.5 chord length. Using the stacking axis as a further support point, the profiles can be completely described by B-splines. In the root section of the blade close to the fillet radius, the profile has a higher thickness decreasing towards the tip. In the tip region of the blade, the profile form is rather straight. Besides the profile form, the leading and trailing edge is designed as an elliptic feature having a tangent-continuous transition into the DCA profile (compare Figure 5, upper right-hand side).

In addition to the aerodynamic features described above, a forward sweep was introduced at the tip of the blade. Features such as forward or backward sweeps or other three-dimensional modifications of the blade like lean and bow were added as challenging features and adjusted based on comments from industry partners (Figure 5). They help to optimize the flow distribution, e.g. away from the tip where losses are more significant at the clearance gap. As the blisk model was not optimized by such means, the sweep at the tip was designed in a qualitative way. The swept tip was introduced into the blisk model as it has a significant impact on the machining, which is further explained in the manufacturing perspective below. Finally, the transition of the blade feature to the hub section is designed as a constant fillet radius. [5]

![Figure 5](https://example.com/figure5.png)

**Figure 5**: Profile twist, form, airfoil leading/trailing edge and sweep defining the blisk model blade

The structure mechanical point of view is not further discussed within this document, however, was regarded in the design process. Here, an analytical estimation was done based on the rotational speed (~12,000 rpm) of the rotor, the centrifugal stress and bending stress with a maximum allowable stress for the relevant range of alloys. [5]

### 2.4. Peripheral Features

In addition to the blade features mentioned above (Figure 5), the blisk model also includes peripheral features such as:

- Seal fins,
- Scallops,
- Bores,
- Fillet radius
- Complex disk shape

An overview is illustrated in Figure 6
The most important geometrical values are summarized in Table 1:

| Feature                  | Value     | Feature                  | Value     |
|--------------------------|-----------|--------------------------|-----------|
| Blade Height (h)         | 100 mm    | Number of Blades (N)     | 30        |
| Chord length (l)         | 45 mm     | Blade Airfoil            | DCA       |
| Hub Radius (rn)          | 120 mm    | Profile Twist (\(\phi\) LE) | 30°      |
| Blade Height (h)         | 100 mm    | Flow Coefficient (\(\psi\)) | 0.5     |
| Hub-to-tip ratio (rn/rg) | 0.545     | Work Coefficient (\(\psi\)) | 0.7     |
| Height-to-chord ratio (h/l) | 2.22 | Enthalpy Coefficient (\(\rho\)) | 0.55 |
| Distance to chord ratio (t/l) | 0.8   | Elliptic-edge-ratio:     | 1-2      |

3. Manufacturing Processes in Scope
The manufacturing of compressor rotors of an integral blisk-configuration ranks among the most difficult processes in turbomachinery, due to its complex geometric proportions, very limited choice of material (such as titanium and nickel-alloys) and very challenging manufacturing tolerances. Nonetheless, there is a variety of different manufacturing technologies that can be utilized in the manufacturing process.

3.1. Three Manufacturing Scenarios Defined
This process evaluation is based on a generalized chain of manufacturing sequence. The generic manufacturing process can be divided into: material generation, disk shaping & testing, feature machining, surface treatment & special processes and quality assurance. Within each process step the specific manufacturing technologies can alter or consist of a different combination of manufacturing sub-steps [9] [10]. Table 2 shows a schematic overview of the three basic scenarios in scope for blisk manufacturing.

| Scenario | Material                          | Manufacturing of Blade Geometry |
|----------|-----------------------------------|---------------------------------|
| #1       | Ti-Blisk, conventionally casted    | Milling                         |
| #2       | Ni-Blisk (Inconel), conventionally casted | Milling                         |
| #3       | Ni-Blisk (Inconel), powder metallurgical | ECM                            |
These three scenarios distinctly differ based on the material selection and manufacturing process choices. The first scenario is defined by a raw material selection of Ti-6Al-4V, which is a common material choice for the front stages of the high-pressure compressor as well as the low-pressure compressor section because of its good mechanical properties and light weight. The blade and flow path manufacturing is done through an advanced milling process, which is a common process for blade machining. The second scenario is defined by a Nickel based alloy conventionally casted as raw material choice. Nickel alloys are used in later stages of the high-pressure compressor due to their high thermal resilience. [5] The blade geometry is also machined through advanced milling. The third scenario is also characterized by a Nickel alloy raw material but the material is generated through powder metallurgical processes rather than conventional casting to investigate the influence of different raw material generations. The blade manufacturing will be done by an Electro-Chemical-Machining (ECM) process as an alternative to the aforementioned milling process.

3.2. Process Chain and Life-Cycle-Inventory
The first manufacturing scenario is visualized as an example in Figure 7 and serves as an example for a process flow chart for a subsequent Life-Cycle-Analysis. It includes all relevant process steps from melting to quality assurance.

The data for the Life-Cycle-Inventories (LCI) is presently being acquired for each individual process step. These include input and output flows such as: electrical energy, compressed air, cooling liquids as well as waste e.g. chips, slag and evaporated coolant. To ensure proper data quality the acquisition will follow the real manufacturing process. Previous studies which have been conducted in the past may be included as background data for particular details e.g. for milling tools [11].
4. Summary & Outlook

This paper has described the geometry model of an engine compressor blisk and the three scenarios selected for a Life Cycle Assessment approach on a full size compressor blisk. The model was designed based on basic analytical calculations and discussed with partners from the industry. It serves as a carrier of ambitious features from a manufacturing perspective such as complex blade geometry including large twist, forward sweep, DCA-airfoils and elliptical edge and a disk geometry with bores and scallops. An aerodynamical- and structural-mechanically optimization on a numerical level has not been included.

The three manufacturing routes which have been defined for the Life Cycle Assessment are: a route for a Titanium blisk conventionally casted and with its blades milled, route for a Nickel-alloy blisk conventionally casted and also with its blades milled and a route for a Nickel-alloy blisk with powder metallurgical material generation and ECM-based blade manufacturing.

All process routes will be included for Life Cycle Assessment to derive their Life-Cycle-Impacts [12]. This will be conducted as part of the ecoDESIGN Transversal Activity in Clean Sky 2 and also following the recommendations by the United Nations [13] and by the European Union [14]. Details and results will be provided as part of future publications.

Acknowledgments

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation program under grant agreements No807085 and No945541. Special acknowledgement to the industrial community represented in the workshops of this project.

References

[1] Pearce B. 2020 COVID-19: Outlook for air travel in the next 5 years https://www.iata.org/en/iata-repository/publications/economic-reports/covid-19-outlook-for-air-travel-in-the-next-5-years/
[2] Knörzer D, Warsop C, Diaconescu C, Sanfourche JP (ed) 2015 Aviation in Europe Innovating for growth proceedings of the seventh European Aeronautics Days (London)
[3] Hubig C 2012 Fertigungsgerechtes Konstruieren von Hochdruckverdichterschaufeln in Blisk-Bauweise (Schriftenreihe des PTW) (Aachen: Shaker)
[4] DiOrio A 2012 Small Core Axial Compressors for High Efficiency Jet Aircraft Master Thesis MIT
[5] Bräunling W J G 2015 Flugzeugtriebwerke: Grundlagen, Aero-Thermodynamik, ideale und reale Kreisprozesse, thermische Turbomaschinen, Komponenten, Emissionen und Systeme (VDI-Buch) 4th edn (Berlin: Springer Vieweg)
[6] Goodhand M N 2010 Compressor leading edges Apollo - University of Cambridge Repository University of Cambridge
[7] Loh W H T 1968 Aerodynamic Design of Axial Flow Compressors and Turbines Jet, Rocket, Nuclear, Ion and Electric Propulsion (Applied Physics and Engineering) ed W H T Loh and W H T Loh (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 207–35
[8] Dixon S L and Hall C A 2014 Three-Dimensional Flows in Axial Turbomachines Fluid Mechanics and Thermodynamics of Turbomachinery (Elsevier) pp 215–63
[9] Klocke F, Zeis M, Klink A and Veselevac D 2013 Technological and economical comparison of roughing strategies via milling, sinking-EDM, wire-EDM and ECM for titanium- and nickel-based blisks CIRP Journal of Manufacturing Science and Technology 198–203
[10] Klocke F, Schmitt R, Zeis M, Heidemann L, Kerkhoff J, Heinen D and Klink A 2015 Technological and Economical Assessment of Alternative Process Chains for Blisk Manufacture Procedia CIRP 67–72
[11] Grünebaum T, Müller U, Rey J, Barth S and Bergs T 2019 Life cycle oriented technology chain optimization: a methodology to identify the influences of tool manufacturing on environmental impacts caused in the tool’s use phase Prod. Eng. Res. Devel. 13 567–77
[12] Lüdemann L and Feig K. 2015 Comparison of software solutions for Life Cycle Assessment (LCA) – a software ergonomic analysis Logistics Journal
[13] Frischknecht R et al 2016 Global guidance on environmental life cycle impact assessment indicators: progress and case study Int J Life Cycle Assess 21 429–42
[14] European Commission 2010 ILCD handbook: General guide for life cycle assessment : detailed guidance (Scientific and technical research series EUR 24708) (Luxembourg: Publications Office of the European Union)