Performance and Functionality Based Design Methods for Improved and Novel Aircraft Engine Components for Additive Manufacturing

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Abstract

For aircraft engine manufacturers the technology of AM appears promising. AM provides the opportunity for a highly flexible and a cost effective part production. Furthermore AM offers new potentials and possibilities for lightweight designs. The implementation and applications of AM can be divided in three different strategic application levels. The first level includes manufacturing simple existing parts; these kinds of parts are already in production. In the second level, new design tools, such as structural optimization, are used to improve an existing part by benefiting from the new design freedom but without changing its functionality. The third level includes novel parts with new functionality.

This paper presents design methods for AM parts for the second and third level: performance and solution based approach, respectively. Also the safety classification of engine parts is looked into. Step-by-step design methods are presented, accompanied by case studies that demonstrate improvement to the initial design: a light weight, topology optimized turbine guide vane (level two) and an aircraft engine casing design that has an improved tip clearance behavior under transient operating cycles (level three).

Introduction

Additive manufacturing (AM) has been highly interesting for the aircraft engine manufacturers in the recent years and several aircraft engine manufacturers are active [1], [2]. The main benefits of AM in aircraft engines are more economic part production, lightweight design by complex geometries as well as new integrated functionalities. However, the production of components by AM and use in regular flight operation is still behind some barriers.

An aircraft engine manufacturer is looking for an AM application that offers a clear benefit over the current way of manufacturing but with the same level of safety of the aircraft. The safety must be proven by the engine manufacturer. For example, turbine discs are required by authorities not to fail during their life. To prove this, only very little deviations in the material properties and manufacturing quality are allowed. Sufficient fatigue strength tests of AM materials or tests proving the repeatability of the achievable material properties have not been published yet. Moreover, modern high pressure turbine blades are highly loaded due to rotation and maximum gas temperatures of 1700 K and higher [3]. Only materials with single crystal properties can provide the required performance and durability under these conditions [3]. In that case, AM is also required to produce single crystal material properties.

On the other hand, the AM community is actively looking at applications in the aerospace industry [4], [5], [6] but the focus has been so far on the manufacturing itself, support structures and geometrical tolerances. Additional but for the aircraft engine industry essential topics are the fatigue life of AM parts and the repeatability of the part quality. Until these barriers have been overcome, we look at hot end parts that have less critical classification or are non-rotating to reduce the risk of high cycle fatigue failure.

In this paper, the qualification and classification of aircraft engine components is shortly presented. Examples for AM are pointed out. The examples are categorized in levels of application of AM. Two examples are presented in more detail.

Qualification process and classification of aircraft engine parts

Safety classification of aircraft engine parts results from the ultimate objective, that the risk to the aircraft from all engine failure conditions is acceptably low. An engine part, whose primary failure can hazard the aircraft or injure people, is specified as a "critical part" [7], [8]. Additionally, it is stated that design precautions must be taken to minimize the hazards to the airplane in the event of an engine rotor failure. Turbine disks, the most massive and also expensive rotating components in an aircraft engine, are an example of a critical part. The disk transmits the torque to the shaft and has to withstand the entire load from all of the attached blades. Therefore a turbine disk failure can destroy the casing (uncontained failure) and can release high-energy engine debris capable of damaging an airplane and endangering its passengers.

In order to avoid such a hazardous failure it is necessary to meet specific integrity requirements for critical parts over the entire product life cycle. A manufacturing and an engineering plan identifies the specific constraints necessary to consistently produce critical parts. They include the operating loads and conditions, specific manufacturing process constraints and material properties, all validated by analysis, test or service experience. In case of AM parts sufficient data for the manufacturing and engineering plan are not yet available.

Other engine parts whose primary failure may seriously impair the performance of the engine are often classified as "sensitive parts" [7], [8]. For all classified parts it is imperative to have reproducible properties and a traceability system, starting from design process through manufacturing, assembling, operations and maintenance. Otherwise, no certification according to the requirements announced by authorities is possible.

Design process for AM parts

Additive manufacturing can be used for several purposes in the aerospace industry. Due to the demanding certification process, established manufacturing methods are hard to replace. Thus, a clear benefit over the state-of-the-art manufacturing methods must be demonstrated. One low-risk strategy in AM part development in aircraft engine components is to start with test rig equipment then coming to substitution of existing parts and finally moving in the manufacturing of novel parts [1]. The parts mentioned in this paper are now categorized by the obtainable benefit which is also related to the complexity of the design process. Arranged by the complexity of the design process and starting from the simplest, the three levels of applications of AM for aircraft engine components can be listed as in Table 1.

Level	Objective	Description	Examples
1	more economic production, integral design	Recreation of the part for AM	Tools with complex geometry, TiAl-Blades [5], Inserts for borescope access [1], Fuel injectors [9]
2	modern light weight design	Geometrical modifications to improve the design	LP turbine guide vane [10] Brackets [11]
3	new functions, functional structures	Creation of a novel part	Auxetic engine casing [12], [13], [14]

Table 1 Levels of AM application in the aircraft engine

First, more economic production can be achieved by reducing the amount of parts by integral design [1] or by benefiting from the ability of AM to manufacture materials that are otherwise difficult to manufacture, such as TiAl low pressure turbine blades [5]. Another big advantage is that AM does not waste significant quantities of material. When manufacturing with expensive or rare elements, this ability will play the dominant role.

Second, existing parts can be made more efficient by reducing the weight by integral structures or new lightweight design which can be achieved either by using modern optimization tools, such as topology optimization, or new kind of light weight material, such as mesoscopic lattice structures. Topology optimization (TO) is based on the finite element method, where the elements are the design variables of the optimization problem [15]. TO enables to create light weight concepts by generating an efficient structure (also called bionic design). It has been applied in aircraft engines already to various brackets [11], [1]. This design method requires more effort than the previous one but once established, it can be applied to a myriad of aircraft engine parts to reduce weight.

Third, the design freedom of AM allows the realization of novel parts with improved functions. Such functions add value by including new features that improve the product performance, for example functional structures which minimize the radial gap between rotating and non-rotating parts and therefore improve the clearance behavior at all operating points and thus improve the overall aircraft engine efficiency [12]. This design method requires carrying out a complete design process and is thus considered as the most complex.

Design method for modern light weight design: Low pressure turbine guide vane

Low pressure turbine guide vanes (TGV) are an example of a level two part. Compared to the forged compressor blades and vanes, where aerodynamic design leads to a thin body, the turbine blades and vanes are made by casting, and heat transport phenomena become more important. Therefore the solid vane body of a TGV is relatively thick which enables a greater advantage of lightweight design by the use of hollow structures.

The function of a TGV is to guide and accelerate the flow, which results in bending forces at high temperature. Relevant damage mechanisms are thermo-mechanical fatigue due to engine start-shutdown cycles as well as creep.

A design method for topology optimization and additively manufactured parts was proposed by Emmelmann et al. [6]. The design phase consists of topology optimization for light weight design, followed by the "interpretation of results" and "remodeling in 3D-CAD" where a new geometry is modelled manually by identifying types of substructures according to their type of loading. The interpretation and remodeling can be very time consuming but it is necessary with the currently available software tools.

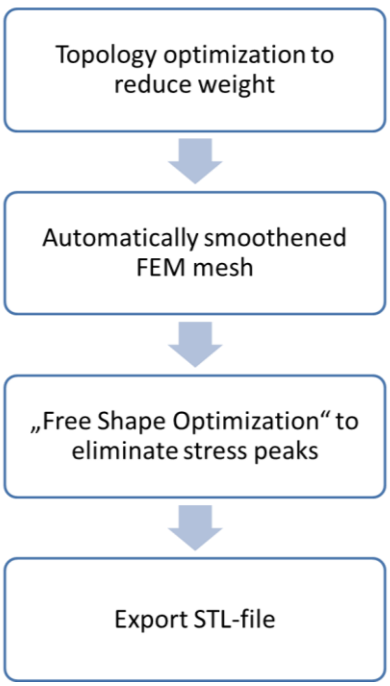

Figure 1 Workflow for topology optimized components

The design workflow used here, shown by Figure 1, starts with TO, followed by a geometry transfer step and a shape optimization. The aim is to reduce manual work after TO. The goal of the topology optimization is mass minimization.

In the setup of TO, the finite element model is divided in design and non-design spaces. The design space is the optimization domain. The non-design space consists of all surfaces with aerodynamic relevance as well as of interfaces with other parts. Thus, the domain for design improvement is limited to the interior of the vane. The influence of the hot gas is considered by using material properties at corresponding temperature.

The resulting geometry generated by TO can be seen in Figure 2. The result is a distribution of artificial density. The solver (Altair OptiStruct) strives for a discrete design (solid material or void) but the amount of intermediate densities is dependent on the optimization setup and cannot be avoided completely. Thus, a selection between solid and void has to be made after TO by the user. The topology is smoothened by an included tool and a shape optimization is conducted to reduce stress peaks. The final geometry will be exported from the FEM model in STL format.

A certain axial gap between the TGV and the following rotor blades is required in order to avoid collision. The lowest five Eigen frequencies are not allowed to sink in order to remain in the frequency range for which the original component was designed.

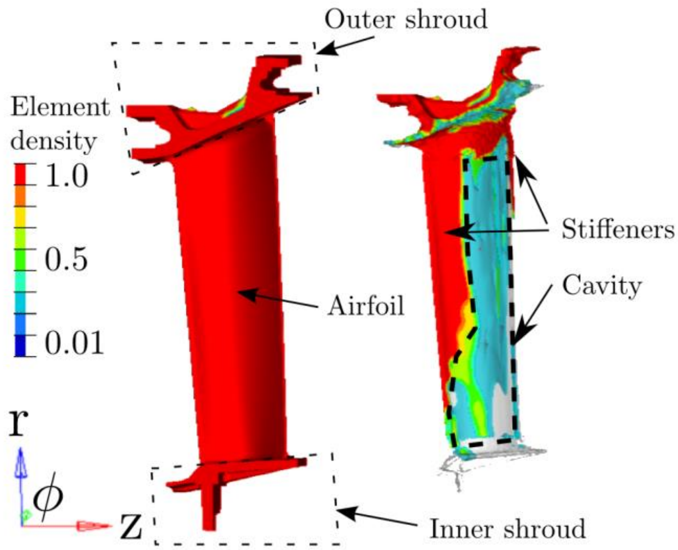

Figure 2 Result of a topology optimization of a turbine guide vane. Left: exterior of the vane (non-design space), right: interior of the vane (design space) [10]

An improved result – more weight reduction - in the topology optimization can be obtained if the optimizer is given more design freedom – in fact the complete design space that is available in the assembly [10]. In the case of the TGV, there is an unused space between the casing and the TGV as shown by Figure 3. The unused space can be allocated in design space for the optimization.

After the optimization, changes to the geometry will be done manually to enable additive manufacturing. The changes include determining the optimal build direction so that the amount of support structures on the outer surfaces is minimized for an economic production. The interior of the vane is evaluated in the selected AM build direction and overhangs larger than the allowable angle are identified. The identified area is now manually reconstructed so that no supports are required in the inside. This of course results in a deviation from the optimal geometry.

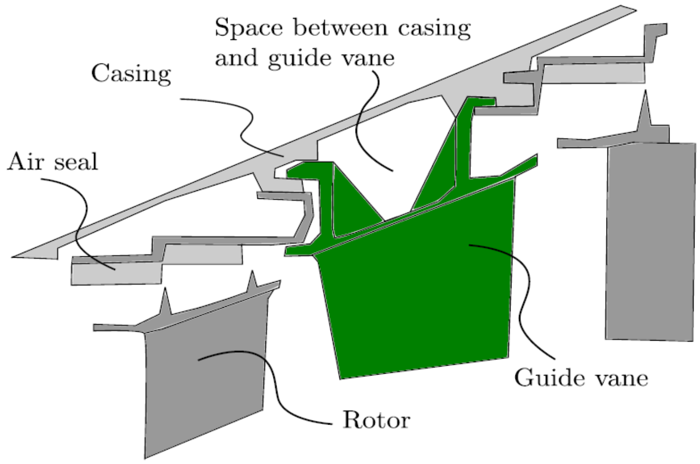

Figure 3 Indication of unused space in the guide vane assembly [10]

Concluding, the workflow of level two parts is presented in Table 2.

Part selection	- non-rotating part - cast component, no special microstructure required - turbine vanes have thicker airfoils than compressor ones
Topology optimization	- Definition of design and non-design space: What functionalities are required, first decisions on the build direction, unused space in the assembly - Other requirements (optimization constraints): bending deformation, stress, Eigen frequencies - Objective: minimization of mass
Smoothening	- Smoothen the TO result into a smooth FEM mesh
Shape optimization	- Identify and minimize stress peaks by nodal perturbation at the outer surfaces
CAD	- Manual construction of a final 3D CAD model by considering the manufacturing considerations: overhangs, powder removal

Table 2 Workflow for level two components: improvement by modern light weight design tools

The result of the topology optimization showed a weight reduction of 19% while the stress due to gas loads increased only 4% [10]. Thus, there is potential for weight reduction by using this method. In the case of the low pressure turbine guide vane, thermal stress also needs to be considered, which is being currently implemented in the workflow. This design method can also be used to reduce the weight of other parts that have functional surfaces but unused material inside. Further work includes the implementation of overhang penalization in TO.

<u>**Design method for parts with new functions: auxetic compressor casing**</u>

The next example is a double-walled casing design with auxetic structures (negative poisons ratio) between the inner and outer casing wall of a compressor with the purpose to adapt the radial expansion behavior of the casing to the one of the rotor. The tip clearance s/h is indicated in Figure 4.

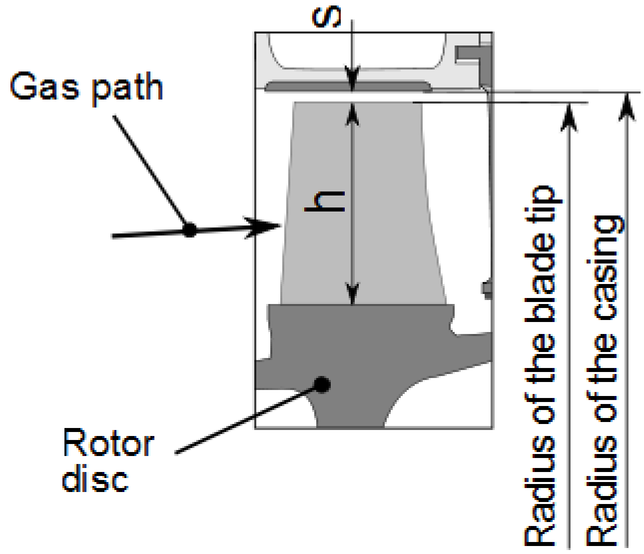

Figure 4 Tip clearance s/h

The intention is to develop a passive tip clearance system to reduce volumetric losses caused by flow that passes the airfoils through the radial tip gap s. First, the most promising auxetic casing geometry is identified in a concept study. The geometrical parameters of the auxetic structure, as depicted in Figure 5, are varied with the purpose to find the influence of each parameter on the radial deflection behavior of the casing and to adapt the casing to a certain rotor characteristic. [12]

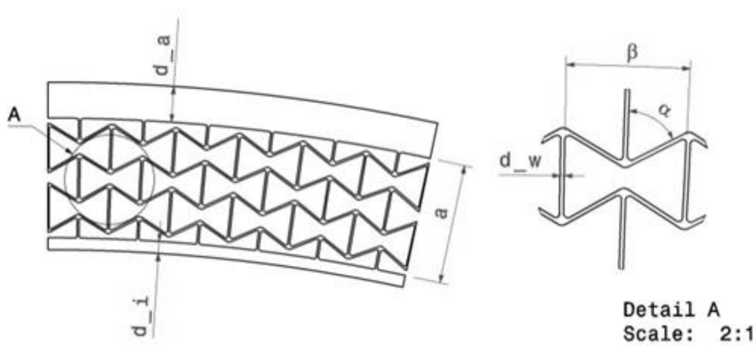

Figure 5 Geometrical parameters of the auxetic structure [12]

By simulating the characteristics of the radial displacement of the rotor and the casings, the tip clearance behavior is calculated by a thermo-elastic finite element analysis with a nominal (cold) tip clearance of *0.5 mm*, as illustrated in Figure 6. The radial displacement of the rotor depends directly on the centrifugal forces and is thus increasing rapidly with the rotational speed. The thin casing is responding to the thermal loading more slowly. This behavior can be seen in Figure 6 as an increase in the tip clearance at the start of the engine.

Basically, the tip clearance of the auxetic casing "*Aux3h*" is considerably lower throughout the entire test cycle than the one of the single and double walled reference casings *"Ref1"* and *"Ref2"*, as shown in Figure 6. The minimum tip clearance of "*Aux3h*" occurs after 300 s due when the deformation of the rotor is already relatively high, whereas the thermal expansion of the casing is still ongoing due to the low heat conductivity of the auxetic structure. The casings *"Ref1"* and *"Ref2"* are expanding more rapidly. After 2400 s the tip clearance is increasing sharply when the load is decreased. The rotor displacement is decreased due to the lowered centrifugal forces whereas the hot casing has a longer lasting radial deflection due to its thermal inertia. The tip clearance is decreased during the following hot reslam (sudden increase to full power). During the following deceleration of the rotational speed the tip clearance is continually decreased. [12]

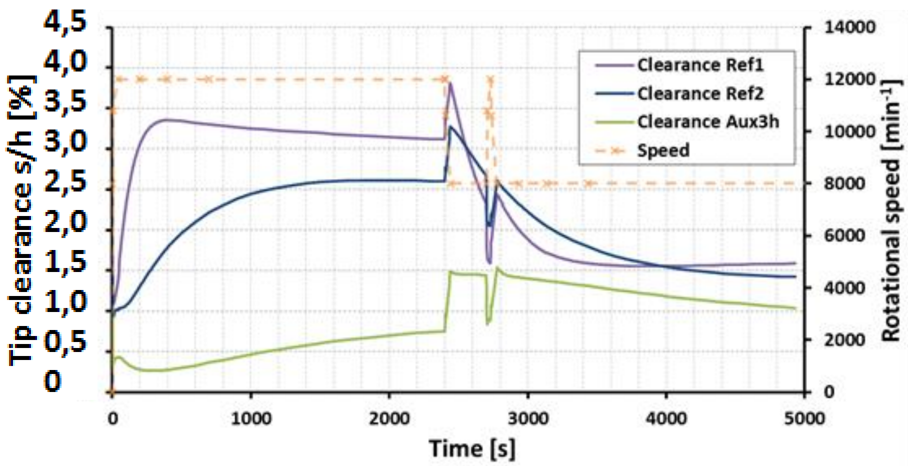

Figure 6 Characteristic of the tip clearance of the casings "*Ref1*", "*Ref2*" and "*Aux3h*" using a nominal (cold) tip clearance of *0.5 mm* [12]

Now, the parameters of the design *"Aux3h"* are varied to gain the optimal tip clearance. The optimized casing behavior is illustrated in Figure 7 showing the radial displacement of the rotor and the casings with different parameters. The radial gap is the difference of the rotor´s and casing´s axial displacement. The optimized casing design "*K1*" reduces the tip clearance significantly throughout the entire test cycle compared to the original design "*Aux3h*". At take-off condition the radial expansion is reduced by 23%. This leads to reduction of the tip clearance s/h by approximately 50%. Thus, the casing "Aux3h" can be adapted to a certain rotor by using suitable geometrical parameters. [12]

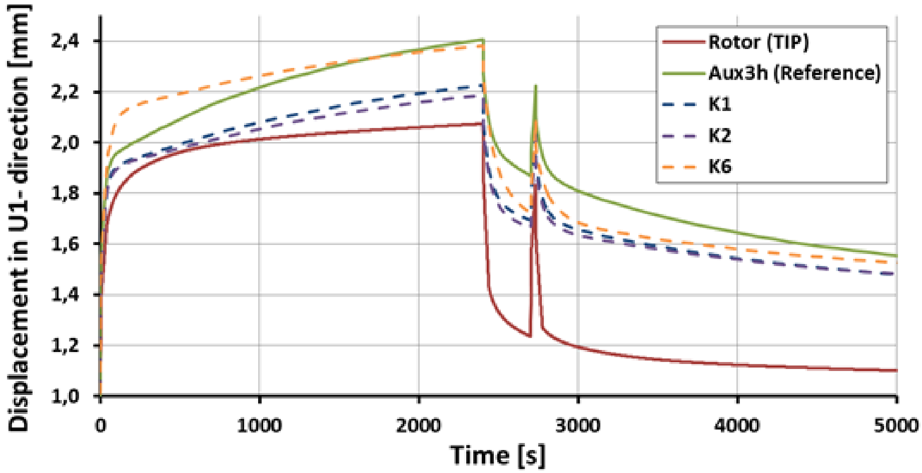

Figure 7 Optimized casing geometries [12]

Figure 8 shows the integration of the auxetic structures in a ring casing design. In a ring casing design, the casing is axially mounted with ring segments. The auxetic structures lead to the necessity of adapting the casing. A higher number of bleed air flanges is necessary since the diameter of the flanges has to be decreased to allow space for the auxetic structures. The design of the outer support structure of the auxetic structure to the outer casing is modified so that openings are integrated in the intermediate casing walls to enable the application of a cooling air supply in the auxetic structure to increase the auxetic effect even further. Openings are inserted in the intermediate casing walls in order to remove the powder resulting from the manufacturing process and in order to have the same pressure in the auxetic structure as at the surface of the outer casing wall. [13]

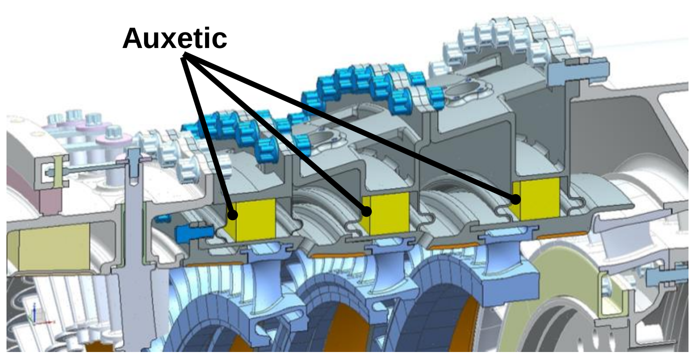

Figure 8 Integration of the auxetic structures in a ring casing [12]

In conclusion, the radial displacement behavior of the initial casing design “Aux3h” is improved in terms of tip clearance minimization. The radial expansion behavior of the casing can be adapted to the one of the rotor by varying the geometrical parameters of the auxetic structure in a certain range in the applied test cycle. The relative tip clearance reduction offers large benefits in both, compressor performance and surge margin (safety of operation). By the use of correct geometrical parameters, it is possible to match the radial expansion behavior of the casing to the one of a certain rotor. The workflow of this design process is listed in Table 3.

List of requirements and challenges in the current design	- Light weight: two walled casing design - Challenge in turbo machinery design: volumetric losses due to changing tip clearances during a mission
Concept design	- Concept study on various auxetic structures that have desired thermal extension
Selection of the best concept	- Simulative demonstration with primitive geometries
Validation with a real mission	- Simulative validation with realistic temperature and pressure conditions on a real geometry - Optimization of the clearance by parameter variation

Table 3 Workflow for level three parts: improvement by new functions

Conclusion

Two design methods for additively manufactured aircraft engine components were introduced. The level two method aims at improvement of existing parts by creating more efficient parts through structural optimization. This method was demonstrated with a light weight low pressure turbine guide vane, which is ca. 19% lighter than the solid vane. The design process can be applied to other similar applications, too. In the future, manufacturing considerations are to be implemented in the numerical optimization process. These include selection of a build direction and limiting overhangs with respect to the build direction.

The level three method starts from a known design issue in aircraft engine compressor design, namely the transient variation of a tip gap in a high pressure compressor. Several casing concepts were evaluated and the functionality was validated by finite element analysis. The functional casing has an improved tip clearance and thus increases the efficiency and the operation stability of the engine. At the moment, the build chamber size of modern AM machines is preventing the manufacturing of a full casing of a large engine. The method can be verified by experimental studies with an additively manufactured casing segment or with an auxetic casing in very small jet engines as introduced in [16].

In the future, further improvements are needed for the examined applications to reach the engine test phase. To mention the most relevant ones, the fatigue life issues caused by the staircase effect needs to be taken care of by a surface treatment. Moreover, a method for the proofing of internal surfaces is required. Also capable software solutions for AM-specific CAE-CAD interfaces are required to speed up the design process.

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