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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 smoothed 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.

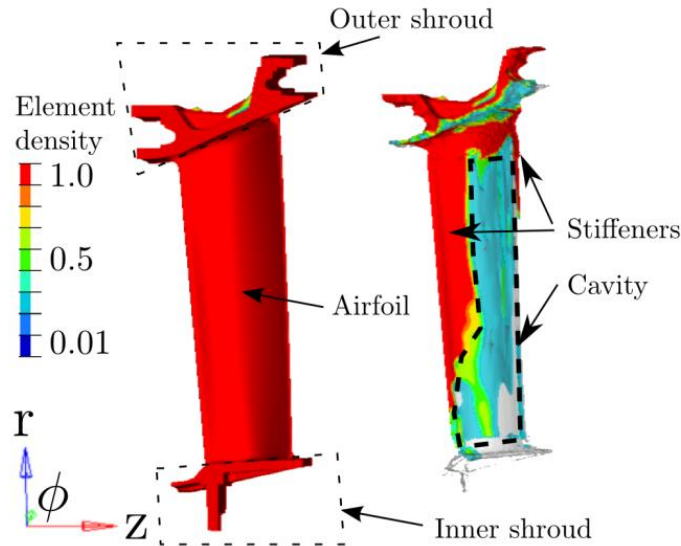


Figure 2 Result of a topology optimization of a turbine guide vane. Left: exterior of the vane (non-design space), right: interior of the vane (design space) [10]

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.

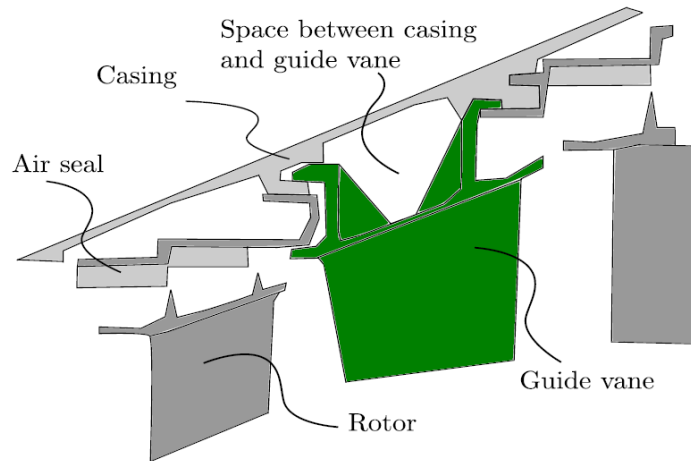


Figure 3 Indication of unused space in the guide vane assembly [10]

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

Part selection	<ul style="list-style-type: none"> - non-rotating part - cast component, no special microstructure required - turbine vanes have thicker airfoils than compressor ones
Topology optimization	<ul style="list-style-type: none"> - 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
Smoothing	<ul style="list-style-type: none"> - Smoothen the TO result into a smooth FEM mesh
Shape optimization	<ul style="list-style-type: none"> - Identify and minimize stress peaks by nodal perturbation at the outer surfaces
CAD	<ul style="list-style-type: none"> - 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.

Design method for parts with new functions: auxetic compressor casing

The next example is a double-walled casing design with auxetic structures (negative Poisson's 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.

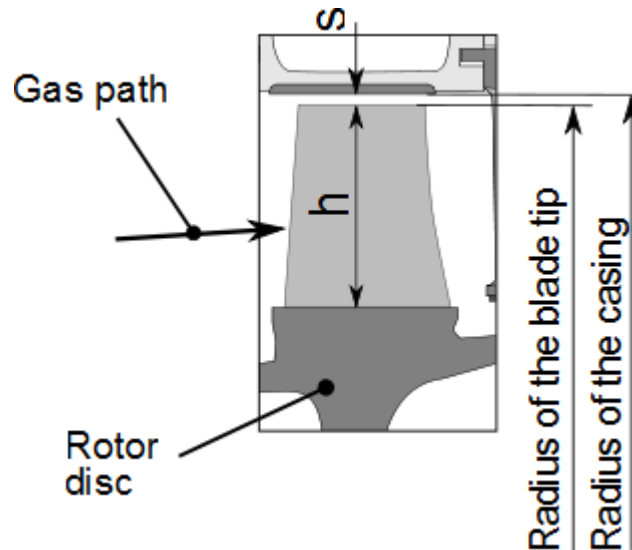


Figure 4 Tip clearance s/h

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]

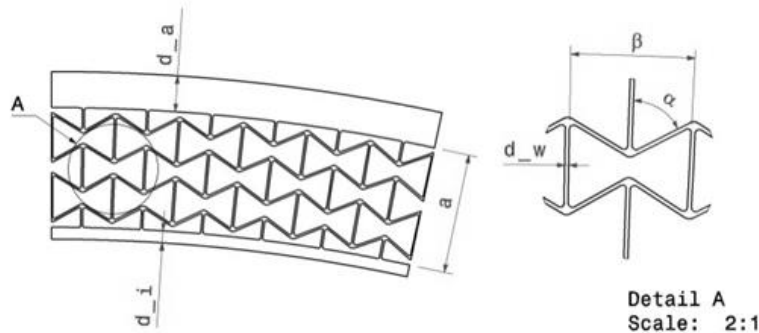


Figure 5 Geometrical parameters of the auxetic structure [12]

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]

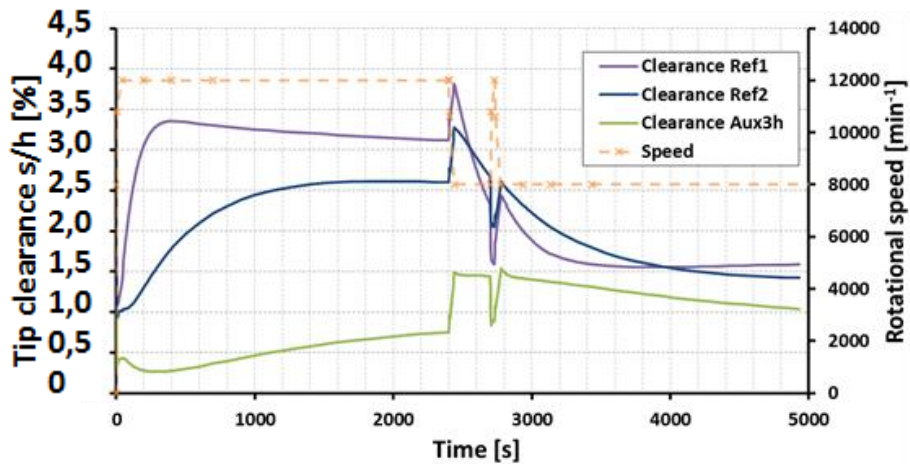


Figure 6 Characteristic of the tip clearance of the casings “Ref1”, “Ref2” and “Aux3h” using a nominal (cold) tip clearance of 0.5 mm [12]

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]

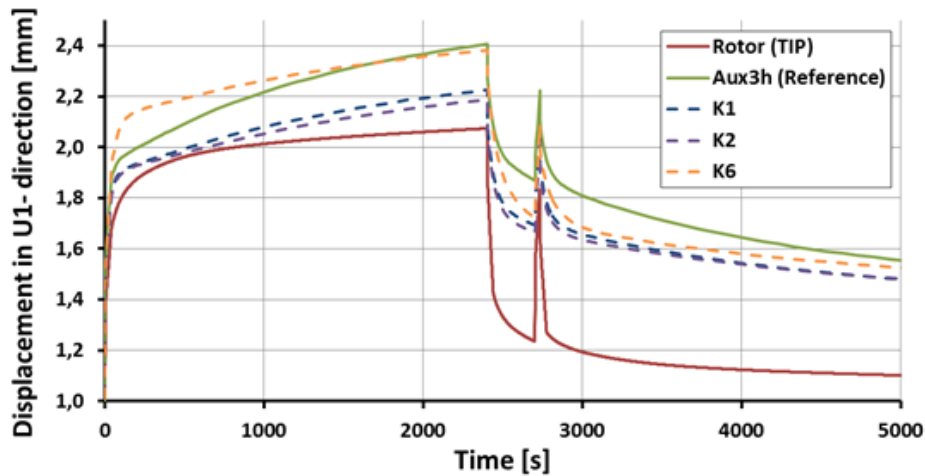


Figure 7 Optimized casing geometries [12]

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]

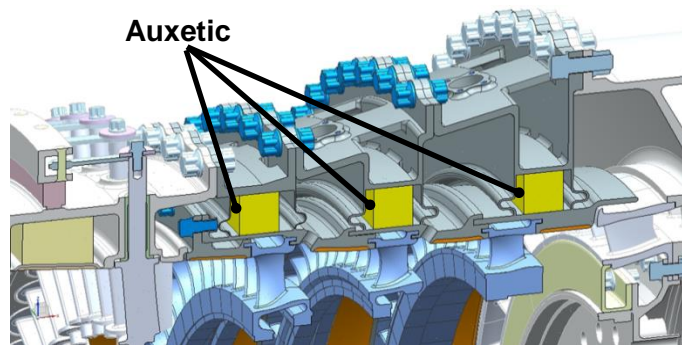


Figure 8 Integration of the auxetic structures in a ring casing [12]

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	<ul style="list-style-type: none"> - Light weight: two walled casing design - Challenge in turbo machinery design: volumetric losses due to changing tip clearances during a mission
Concept design	<ul style="list-style-type: none"> - Concept study on various auxetic structures that have desired thermal extension
Selection of the best concept	<ul style="list-style-type: none"> - Simulative demonstration with primitive geometries
Validation with a real mission	<ul style="list-style-type: none"> - 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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