Optimization of Large-scale Aeroengine Parts Produced by Additive Manufacturing

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Additive Manufacturing (AM) presents a ground-breaking opportunity to produce lightweight parts with enhanced functionality and design flexibility. It revolutionizes assembly by enabling integrated designs that significantly reduce component counts, minimizing assembly efforts and potential faults. Consequently, AM stands out as an appealing choice for manufacturing aerospace engine parts. Among AM techniques for metal parts, Laser Powder Bed Fusion (LPBF), also known as Direct Metal Laser Melting (DMLM), currently dominates the industry due to its capability to achieve high part quality and density using advanced machinery. However, limitations in part size stem from the build envelopes of these machines. Hence, this study explores the feasibility of printing large-scale engine parts, covering the design process, additive manufacturing, and aerothermal testing. A turbine center frame, nearly one meter in diameter, serves as a demonstrator case. Employing a multi-objective Design for Additive Manufacturing (DfAM) approach, the frame's structure underwent optimization through generative design, aiming to minimize mass, maximize stiffness, and meet strength requirements. Furthermore, the manifold section of the frame was optimized to reduce system pressure loss within the designated design space. Inconel 718 using LPBF was selected, with initial segments confirming manufacturability. The manufacturing process was fine-tuned for productivity and part properties, establishing design guidelines accordingly. Subsequently, the optimized manifold design underwent successful aerothermal testing on a specific test rig under various flow conditions. The redesigned frame showcased a 34% weight reduction and a 91% decrease in pressure loss while consolidating over 100 parts into one assembly. For the production, two alternatives are discussed. On the one hand, the final design

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was printed using the GE Additive ATLAS, the largest available LPBF system, validating the AM feasibility for large-scale parts under controlled laboratory conditions. On the other hand, a modified design is proposed that allows for the printing of segments on a regular-sized AM machine and a subsequent welding.

I. Introduction

Advanced Additive Manufacturing (AM) offers a solution to the challenges commonly faced in traditional manufacturing methods [1]. In aerospace, the production of large parts typically involves casting followed by machining, leading to prolonged lead times due to intricate designs, complex supply chains and assemblies. In contrast, AM allows for optimized designs for weight and performance, consolidation of multiple parts to integral designs, and a significant reduction in manufacturing time by executing all necessary operations in a unified setting [2].

Leading aerospace companies are today embracing large-format additive manufacturing as an alternative to traditional manufacturing for engine parts. Expanding this approach, the aerospace industry is advancing large-scale additive manufacturing technology for both single and double-aisle aircraft engines. Efforts are directed towards establishing a comprehensive ecosystem for large-scale AM, encompassing machinery, manufacturing processes, material development, and repair technology. This initiative aligns with the goals of ‘Clean Aviation’ aiming for a cleaner, more sustainable aerospace industry, targeting carbon neutrality by 2050 [3].

This paper focuses on advancements in the design, manufacture, and validation of large-scale aeroengine parts.

II. Design Optimization

A Turbine Center Frame (TCF) was chosen as the demonstrator for this study. It comes at about ~1 m in diameter and is the primary structure located between the low and high pressure turbine stages. As such, in operation it is subject to high radial loads of up to 600kN and thermal cycling of 400K for a typical single aisle aircraft engine. In addition, it comprises a manifold section for air transport between outer and inner side. Currently being made by subtractive and forming processes, the manufacture is energy intensive and has a considerably high buy-to-fly ratio, thus Additive Manufacturing could be an interesting option for this part. Optimization goals were set at a weight saving of 30% while keeping the pressure drop in the manifold at least equal to the conventional design.

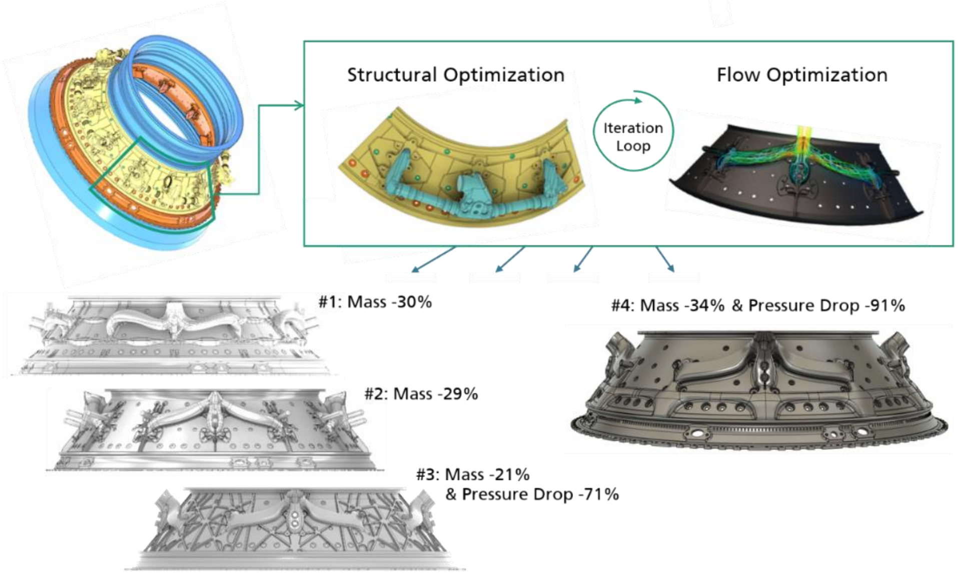


Fig. 1 Design iteration for the Turbine Center Frame.

During the design phase, Generative Design played a pivotal role in arriving at reinforcing elements that could sustain the mechanical and thermal pressures at lowest possible weight. Using multi-physical (mechanical and flow) optimization in an iterative procedure as shown in Fig. 1, different concepts evolved. While outside reinforcements (cf. Fig. 1, concept #3) helped in sustaining all loads, the target weight could only be achieved by changing to an internal reinforcement with a lattice (cf. Fig. 1, concept #4). The final design arrives at a weight saving of 34% and a decrease in the pressure drop of 91%, which is overachieving the target values. Other engineering requirements were also assessed to ensure the additively printed hardware meets its life, HCF, LCF, durability etc.

While the conventional hardware design consists of 100+ individual parts, the optimized frame can be built as single unit.

III. AM Process Optimization

Considering the part's substantial size, the LPBF of the IN718 alloy underwent initial validation using a GE Additive M2 system (GE Additive, Lichtenfels, Germany). For specific details regarding the powder, machine specifications, and process configurations applied, please refer to a previously published source [4]. Fine-tuning the process for density and efficiency, a layer thickness of 60 µm was selected to ensure a reasonable production duration for the eventual full-scale demonstrator. With the selected parameter set, design limits were derived by printing design elements such as walls and struts with varying size and thicknesses, and applying those limits to the final design of the part, as shown in Fig. 2. To conform with the build space restrictions in the M2 system, the parts were slightly scaled down and printed in 1/8th segments first.

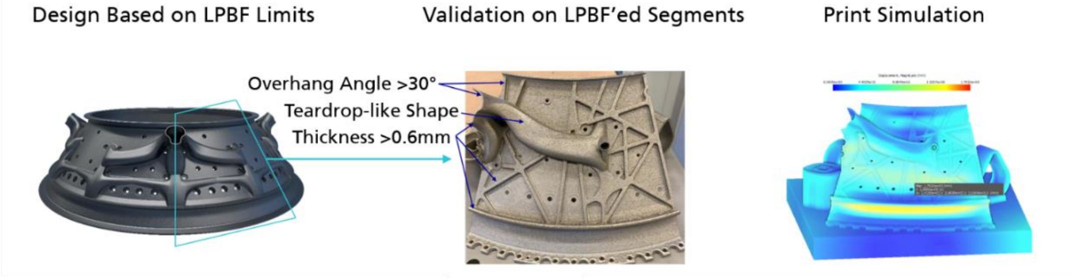


Fig. 2 LPBF Design Limits, applied and validated on 1/8th-Segments of the TCF.

Using build simulation software from Autodesk and using the actual build deformation as validation, it was possible to predict the deformation of the part in good agreement with later builds.

IV. Manifold Aerothermal Testing

Apart from the scaled printed sections, the entire manifold was printed at its actual, full size for subsequent aerothermal testing. However, to produce the component at its original, unscaled dimensions, it was necessary to detach the manifold from the TCF and split it into two separate partitions, cf. Fig. 3 (left, upper part).

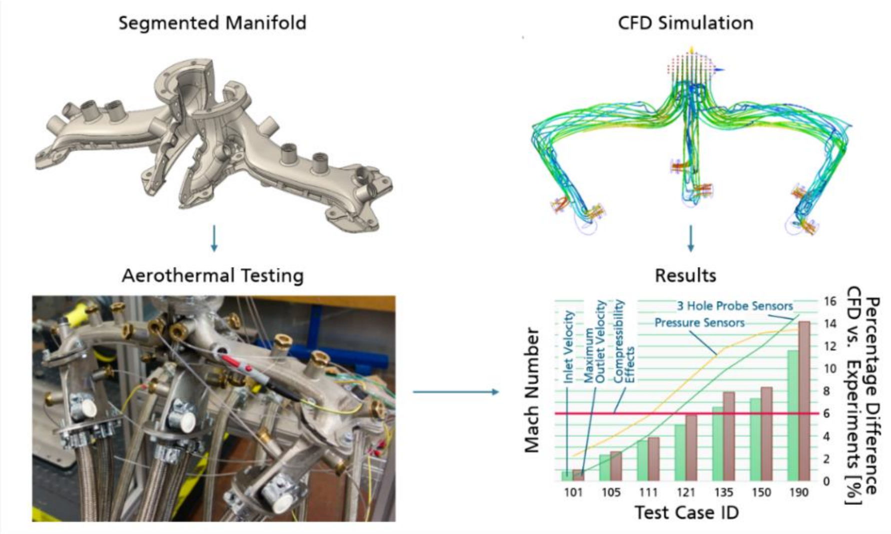


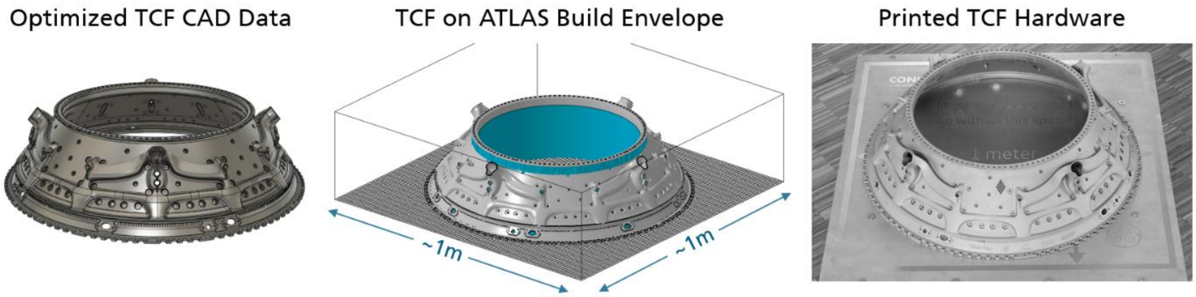
Fig. 3 Aerothermal testing results and comparison to CFD simulations.

To measure flow velocity, specialized three-hole probe sensors were designed and printed by LPBF at AM Metals (Freital, Germany). The calibration methodology adhered to the guidelines outlined in [5]. A comprehensive calibration process encompassed over 50 measurements, resulting in the calibration of a total of fifteen three-hole probes. The integrated sensors in the test-setup are visible in Fig. 3 (left, lower part).

Subsequently, the collected data underwent comparison with the Computational Fluid Dynamics (CFD) outcomes from the design phase, as illustrated in Fig. 3 (right, upper part CFD result; lower part comparison with experimental data). In general, an agreeable alignment was observed between the simulation and experimental results.

V. Manufacturing of Full-size Demonstrator Case

The ultimate design (cf. Fig. 4) was printed at full scale to confirm the entire process from design through manufacturing. Because of its size, the printing occurred using the developmental machine ATLAS (Additive Technology Large Area System) located at GE Additive in Cincinnati, US.


Optimized TCF CAD Data

TCF on ATLAS Build Envelope

Printed TCF Hardware

Fig. 4 Final design of TCF, fitted to ATLAS build envelope, and printed hardware.

No visible cracks appeared in the final built part. With this successful completion, the achievement of TRL 4 and MRL 4 in additive manufacturing for large-scale aerospace engine components has been declared [6]. The findings have been transferred to GE Aerospace (formerly known as GE Aviation) for their subsequent review and evaluation.

VI. Post-Processing of Additive Printed Hardware

Post processing refers to third and final steps in additive manufacturing steps. After manufacturing of large additive part is completed post processing of additive hardware can be a single or set of several steps, these are required to meet quality w.r.t surface roughness, skin texture, tolerance, material structure/strength, defects etc. Multiple post processing steps were identified, optimized and sequenced in a way to ensure that hardware meets its requirements against all engineering need (cf. Fig. 5).

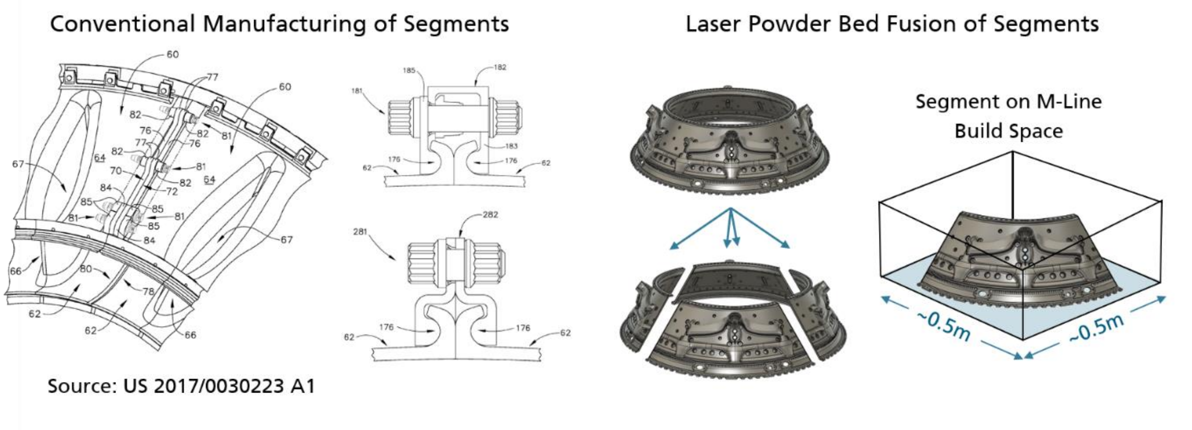
Post processing steps	Purpose
Powder removal	Recycle powder
White/blue light scan	Print distortion prediction
VSR	Stress relief
Wire EDM part off of build plate	Part removal
Support removal	Support structure
Heat Treatment, HIP	Surface/life
White/blue light scan	HIP deformation
Grit blast to remove oxide layer	Surface property
Chem mill	Surface roughness
White/blue light scan	Chem mill distortion
FPI	Material quality
RI	Material structure/strength
Roughness measurements	Final check on roughness

Fig. 5 90° section used for post-processing evaluation (left) and list of post-processing steps (right).

Some of the post processing steps are listed in below table showing the importance to make sure hardware meets its design intended in terms of quality, tolerance and durability. Powder removal is required to ensure there is not trapped powder remains in the hardware which can cause sintering of powder with metal hardware during thermal cycle. 3D scans are required almost after each and every post processing step, this serves as inspection of hardware ensuring to track changes in hardware before and after each post processing step. Vacuum stress relief (VSR) is performed to ensure all stress accumulated in hardware during 3D printing are released followed by hot isostatic pressing (HIP) to regain surface texture and life of component. Chemical etching is performed in additive printed hardware to control surface tolerance of the additive printed hardware which also improves surface roughness. Apart from 3D scans, Fluorescent Penetrant Inspection (FPI), and Radiographic Inspection (RI) were performed to detect defect in hardware. The third and final step in additive printing is important to ensure printed hardware meets engineering requirements, quality and defect free. Fig. 5 (left) shows a 90-degree section printed hardware used to optimize post processing steps.

VII. Hybrid Manufacturing Concept

For components surpassing the typical build sizes of standard machines, typically above 500 mm in one dimension, the current availability of machinery remains limited. Hence, it is advisable to strike a balance between leveraging the advantages of a fully integrated design and creating large segments that fit within standard build volumes. These segments can later be assembled. Fig. 6 (left) shows a general procedure for the assembly of conventionally manufactured segments using spacers and fasteners, as proposed in [7].



Source: US 2017/0030223 A1

Fig. 6 Concept for Additive Manufacturing of Segments and Assembly.

Using Laser Powder Bed Fusion, the TCF can be divided into several segments with the maximum size adjusted to fit the build space of a more regular LPBF system, such as GE Additive M-Line. For automatization purposes, the assembly can be performed e.g. by laser welding. The weld interface can be designed for optimum positioning of the segments and to the requirements of the welding technology used, and printed as part of the segment. A first concept for such a hybrid manufacturing option is shown in Fig. 6 (right).

Depending on the final added assembly costs, this approach might be the more cost-effective solution. Furthermore, adopting this method could facilitate the production of parts using challenging alloys like titanium aluminides, where controlling cooling within a large-scale AM machine poses significant challenges. Thus, it needs to be determined on a case-by-case analysis, whether the full integral printing or the welding of segments is the better option.

VIII. Conclusion

Using a variety of design tools and techniques such as multi-physics Generative Design, CAE & CAM and CFD simulations, a Turbine Center Frame was optimized for weight and pressure drop. The final design which adheres to the design limits of the Laser Powder Bed Fusion Process comes at 34% reduction in weight compared to its predecessor, consolidating over 100 parts into a single component while introducing added functionalities, notably reducing the pressure drop in the cooling channel by 91%. The latter was validated by aerothermal testing on the manifold section, which was successfully used to validate the CFD simulations.

For the manufacturing of the TCF hardware of approximately one meter in size, two options are considered. Firstly, the printing of the full-scale part on GE Additive's ATLAS machine was realized. This represented a significant milestone, being among the largest metal 3D printed parts so far. Remarkably, the Consortium encountered no build issues or potential failures during this ground-breaking printing process. Secondly, a manufacture of segments of the Turbine Center Frame that fit more conventional 3D printer build volumes is suggested. These segments can be printed with modified interfaces for positioning and joining. Laser welding is proposed as a suitable joining method due to its high automation potential. Each option has its own benefits and drawbacks, making it advisable to decide for the best one on a case-by-case base when transferring the results to other large-scale structures.

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