MULTIDISCIPLINARY ROBUSTNESS EVALUATIONS OF AERO ENGINE STRUCTURES

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Abstract

This paper presents a case study made to investigate the functional robustness of a jet engine turbine frame. Using virtual tools, a multidisciplinary analysis involving eight disciplines is performed on 50 non-nominal geometries. These geometries are obtained by varying the positions of the locators in the locating schemes on some parts of the assembly. Results show that geometrical variation can significantly affect the structural stresses on the product, and should thus be investigated further.

Introduction

Turbine structures in the rear end of a jet engine have a range of functional criteria from various fields of engineering. They need to be able to withstand significant thermal and structural loads. In addition, to optimize fuel efficiency, they need to be as light and aerodynamic as possible. These functionality criteria need to be balanced in order to obtain an optimal design.
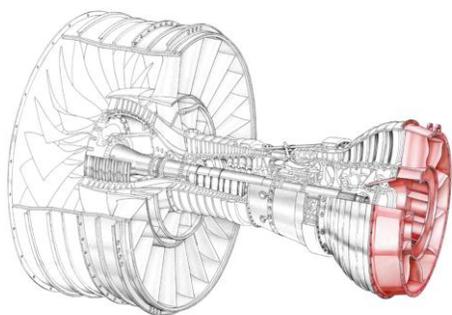
FIGURE 1: Turbine Structure

However, manufacturability criteria are often difficult to quantitatively assess in the design optimization process. As a result, it is often the case that designs optimized from a functionality perspective are expensive or unfeasible to realize in practice. To avoid this scenario, the functionality and manufacturability need to be balanced in order to find the truly optimal design[1]. One of the key limitations of manufacturability is that of geometrical variation, i.e. that the dimensions of a manufactured product deviates from the nominal geometry. Geometrical variation occurs at many stages [2]. Deviations in ingoing parts, as well as dislocations when placing parts in fixtures, propagate through the assembly, and ultimately affect the performance of the engine.

A product whose function is insensitive to geometrical variation is defined to be functionally robust[3]. In aero engine applications, functional robustness is often related to physical phenomena that are coupled. An example given in this paper is the thermal stress stemming from the heating of a turbine structure during flight. Since this problem is dependent on the geometry at hand, it is straightforward to realize that geometrical variation will affect structural strength, which will have an effect on product life length. A geometrical change in the aero surface will affect the convective heat flow into

the material, resulting in a different thermal expansion and life length.

Approaching the above problem requires the use of many engineering disciplines. For a deterministic evaluation of a nominal product, the common approach is for these analyses to be performed in different simulation environments by specialists in each field, with data being manually transferred between them. For robustness and sensitivity analyses, however, this process becomes ineffective and time-consuming[1]. In this paper, an automated, sequential process is suggested for capturing the problem, which allows for parameterizations to be propagated from one end of the analysis chain to the other. A method of combining different analysis methods into a multidisciplinary simulation platform is suggested. This method is then used to investigate the robustness of a generic load carrying rear frame, which is analyzed with respect to thermal stress, as well as structural strength, aerodynamics, weight and manufacturability.

From a technical point of view, the suggested approach means a significantly improved ability to numerically simulate and optimize robustness of component designs with functionality criteria from principally different disciplines. From an industrial application point of view, the suggested approach provides a tool for optimizing new and novel aero engine designs in the preliminary design stage, rather than being treated downstream in the development process.

Scope of paper
This paper looks specifically on how geometrical variation affects structural performance of a turbine structure. After a brief introduction to the central themes of robust design methodology, a case study is presented, where geometrical variation is applied to a turbine structure. A CAD-model, connected to a multidisciplinary simulation platform, is presented. The ingoing analyses types are explained. A Monte Carlo simulation with 50 iterations is set up. The results are visualized in the result section. In the end section, the results are discussed.

Theoretical background

Robust Design
Robust design is a methodology for designing products that are insensitive to variation. According to Phadke [4], product variation can be stemming from raw material variation, manufacturing variation and variation in product usage. Robust design aims at suppressing the effects of this variation without eliminating the variation itself.

Robust design methodology was pioneered by Japanese statistician Genichi Taguchi [5, 6]. Robust design are by some [7] seen as a subset of response surface methodology, which in turn is one of the methods employed in the field of Multidisciplinary Design Optimization(MDO) [8]. MDO also links to neural networks, meta-modeling and kriging [9].

Robust Tolerance Design
Robust tolerance design deals with geometrical variation in parts, fixtures and assemblies. A geometrically robust design is defined by Söderberg [2] as a design that fulfills its functional requirements and meets its constraints even when the geometry is afflicted with small manufacturing or operational variation.

Smith [3] defines robustness as functional insensitivity to stochastic variation. Therefore, how much variation in the assembled geometry that can be accepted depends on the functional requirements of the product. Lorin [10] divides geometrical robustness into three categories: part robustness, assembly robustness and functional robustness. The factors that define these characteristics and how they are related are visualized in Figure 2.
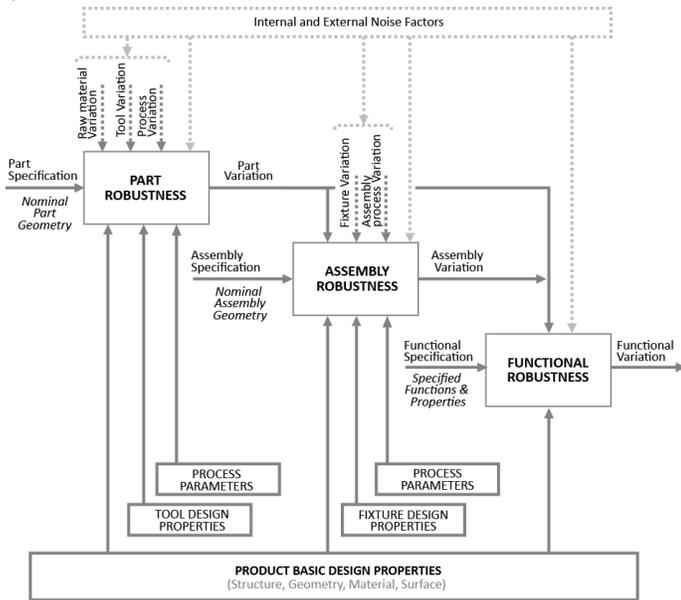
FIGURE 2: Product robustness[10]

Most work on robust tolerance design examines the relation between part variation and assembly variation (the two top boxes in the figure). This paper adds the bottom box to the equation. The functional robustness requirements are dependent on the category of product. In an automotive industry context, work has been done to investigate how geometrical variation influence functional requirements such as ease of assembly and perceived quality [11].

Locating Schemes
The purpose of a locating scheme is to lock a part or a subassembly to its six degrees of freedom in space. Figure 3 shows an orthogonal 3-2-1 locating scheme. The points in the upper right body, the so called *A-points*, control three degrees of freedom: translation in Z, and rotation around X and Y. The two points in the lower left figure, the B-points, control two degrees of freedom: translation in Y and rotation around Z. Finally, the C-point in the lower right figure controls the translation in X. [12]
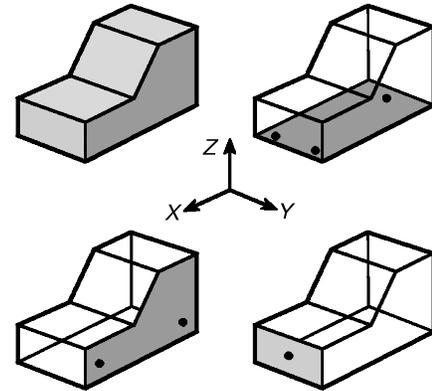

FIGURE 3: 3-2-1 locating scheme

When attaching a part to an assembly, all six degrees of freedom needs to be locked. The part's local positioning scheme, or local p-frame, should be matched by a target p-frame, as shown in figure 4.
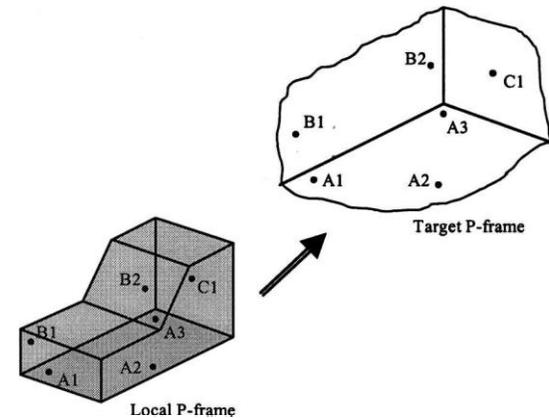

FIGURE 4: Positioning of a part

When examining assembly variation, the locating points should be the points where the part is being held in place by the fixture. Applying variation to the locating points will then affect the positioning of the parts, and therefore, the selection of locating points should be made to minimize the effects of variation on the part position stability [2]. Automated ways of optimizing locating schemes has been put forth [13], as well as well as methods for optimal allocation tolerances on these locating points[14].

Case study

This section presents a case study that connects geometrical variation in a turbine structure with its functionality, thus investigating the functional

robustness of a given turbine structure design.

The turbine structure is shown in figure 5. The structure is a fabricated assembly, consisting and 13 guide vane T-sections and corresponding hub sections. Two of the T-sections have mount lugs, which are used to attach the aft section of the engine to the aircraft pylon. Ring-shaped flanges are attached to the front and back of the shroud. The parts are placed in fixtures and welded together.

FIGURE 5: Turbine structure CAD model

In this case study the design space was limited to the assembly of the two mount lugs. The mount lugs are mounted in fixtures and welded to the assembly.

The locating scheme of the T-section is shown in figure 6. To these points, small variation was applied.
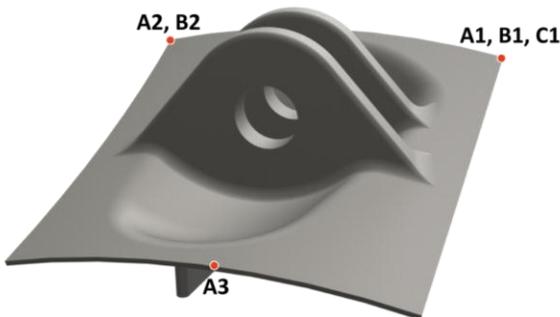

FIGURE 6: Part Locating Points

The CAD-model then underwent a virtual welding procedure to connect the mount lugs to the assembly. This welding procedure consisted of sweeping surfaces to create a solid weld between the interfacing parts. Although this procedure is hardly a realistic depiction of the welding process, the final result is nevertheless a fully connected assembly that can be used for applying variation to parts. Figure 7 shows a realization of such an assembly, when variation is applied on the locating points. The variation, which can be seen on the connecting edges, is exaggerated for visualization purposes.
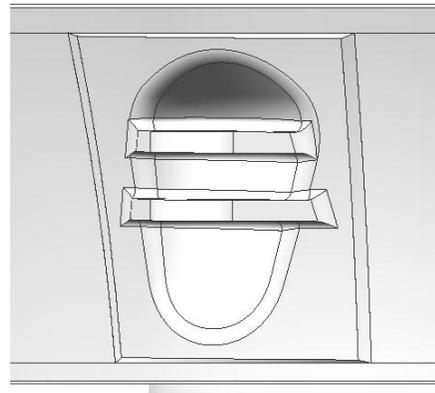

FIGURE 7: Assembly variation can be seen in the connecting edges

Integrated simulation platform

The turbine structure has a range of functionality criteria from various fields of engineering. In this case study, an integrated simulation platform was used to examine these multidisciplinary criteria. Figure 8 shows the workflow of the platform.

The platform uses the umbrella software Ansys Workbench, where parameterized cad models created in NX can be batch processed through meshing and FEM-analyses. The process is fully automated and follows the traditional workflow for verification of turbine structures.
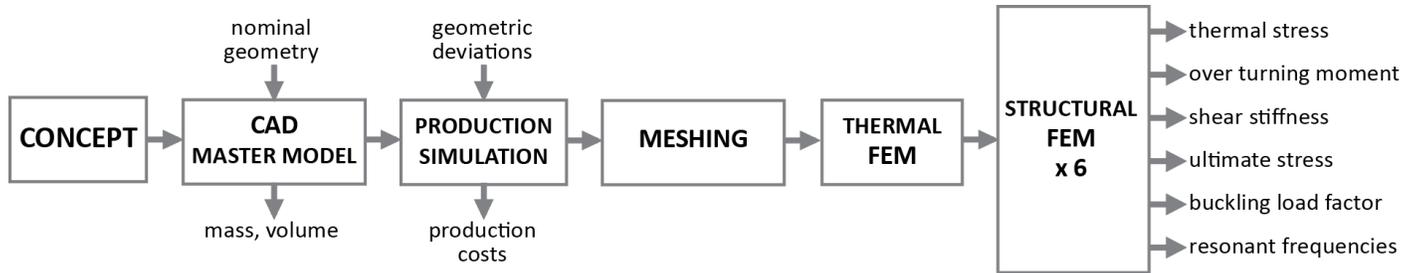
FIGURE 8: Integrated simulation workflow

Analyses

Seven different tests were carried out:

1. Weight analysis – calculates structural weight.

2. Thermal analysis – calculates the material temperature from given boundary surface temperatures.

3. Thermal stress – The recurring thermal loads on the frame create large stresses in the material. This is a limiting factor for product life. Consequently, the thermal stress gives an indication of estimated life. Centerline shift, the movement of the motor shaft centerline because of thermal expansion, was also calculated.

4. Ultimate stress– this assesses whether the turbine structure can withstand extreme events, such as a loss of a fan or turbine blade, or a wheels-up landing. The engine doesn't need to be operational after such an event, but the engine must not separate from the wing, and no parts should be lost. Ultimate stress is measured on the primary and secondary load paths.

5. Shear compliance – calculating the inverse of the stiffness of the product, when a unit load is acting on the bearing housing. Compliance is chosen instead of stiffness to consistently define the output as something that should be minimized.

6. Overturning moment – similar to shear compliance, but instead of a force, a torque on the bearing housing around the airplane's pitch axis.

7. Modal analysis – calculates the Eigen modes of the structure. The frequencies of these Eigen modes should be far from the engine RPM to prevent resonance of mechanical loads, something that can have severe consequences.

Experiment set-up

In order to investigate the geometrical robustness of the design, a Monte-Carlo analysis was performed where the six locating points of each mount lug were varied in their respective degrees of freedom as independent Gaussian variables. In total, there were 12 input variables. The standard deviation of each input was set to ±1 mm. Applying this variation corresponded to translating and rotating the mount shrouds, and reshaping the weld sweeps parts accordingly, to keep the assembly connected. Although this variation is somewhat exaggerated, it provided at conservative estimation, especially as the number of Monte Carlo-simulations were comparatively low.

A Design of Experiments (DOA) approach was considered, but abandoned since the number of inputs was relatively large, and that linear behavior couldn't be assumed. For instance, a two-factorial DOE would have meant 4096 simulations.

In total, Monte Carlo simulation with 50 iterations were performed. Each simulation took approximately 40 minutes.

Table 1: Monte Carlo simulation results

		Unit	Nominal	Mean	Min	Max	Stand. Dev.	Distribution , 50 runs (■ nominal value)
Mass		kg	228.932	228.933	228.891	228.972	0.015	
Thermal Stress	Reg Strut	MPa	340.370	347.257	334.685	364.080	9.174	
	Mount Hub Left	MPa	239.306	236.589	217.852	250.625	7.819	
	Mount Hub Right	MPa	246.678	244.821	222.219	261.663	8.457	
	Mount Shroud Left	MPa	371.857	481.181	207.623	1131.246	204.206	
	Mount Shroud Right	MPa	626.020	684.997	597.622	1383.547	167.110	
Centerline Shift		mm	1.343	1.344	1.337	1.351	0.003	
Overturning Moment		nm/N	217.951	217.966	217.639	219.005	0.363	
Shear Compliance		nm/N	5.895	5.934	5.867	5.999	0.032	
Ultimate Load	Primary Load Path	MPa	473.497	664.922	432.402	1311.888	216.622	
	Secondary Load Path	MPa	640.322	621.906	588.867	650.312	17.334	
Resonant Frequencies	1st	Hz	144.216	143.421	142.789	144.412	0.500	
	2nd	Hz	239.084	238.592	237.560	239.960	0.569	
	3rd	Hz	265.780	264.216	261.564	266.214	1.226	

Results

Table 1 shows the results from the Monte Carlo simulation.

Some of the outputs are almost unaffected by the geometrical variation of the mount lugs. Mass, centerline shift, overturning moment and resonant frequencies all show variation of less than 1%.

From the histograms on the right side of the figure, we note that the distribution functions are very different from each other. For a perfectly linear input/output relation, Gaussian input parameters should yield a Gaussian output. The mass and centerline shift seems to be roughly linear. For a fully optimized geometry, each variation should yield a result that is worse than the nominal. As all outputs (except the resonant frequencies) are desirable to minimize, an optimized design should have the orange nominal bars to the left side of the histogram. This is true for many of the output, for example

the ultimate load-primary load path.

The thermal stresses are all affected by the variation. The parts to which the variation was applied – the mount shrouds - are the most heavily affected. The primary load path in the ultimate load scenario is also heavily affected by the variation.

Figure 9 and 10 compares the thermal stress levels for the nominal geometry with the maximum stress levels, for the left and right mount shroud, respectively. The variation doesn't affect the overall stress levels in the part in any significant way. However, the stress levels on one of the edges are almost doubled on the right part and tripled on the left part.
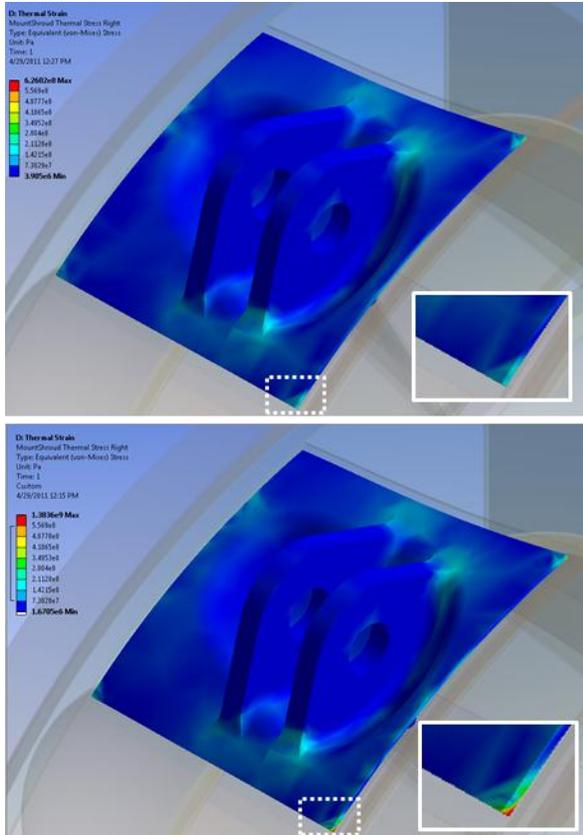
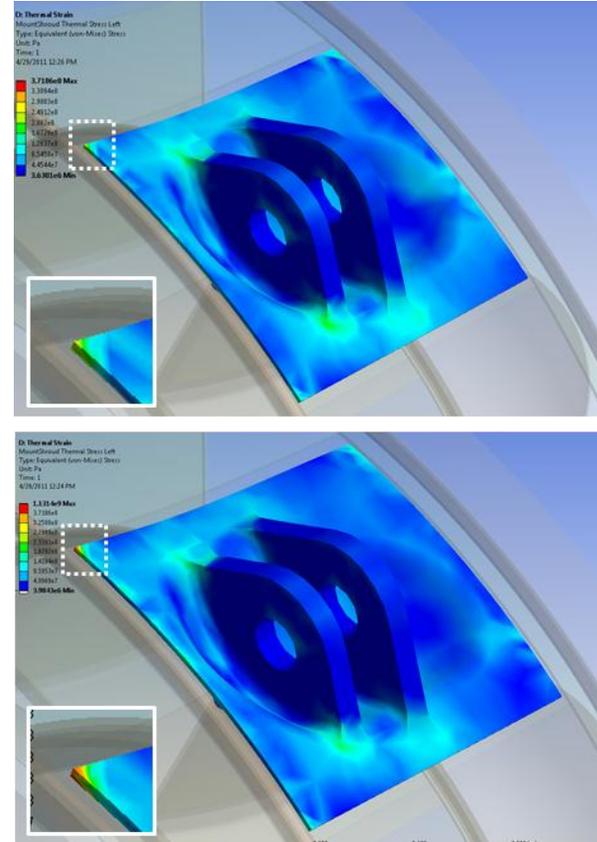FIGURE 9: Thermal stress, nominal
and max, left mount shroud

FIGURE 10: Thermal stress, nominal
and max, right mount shroud

Conclusions and discussion

The results showed a significant variation in some of the functional characteristics as a result of geometrical variation. The conclusion should be made that geometrical variation and its effect cannot be neglected in product development – working only with nominal geometry in simulation is insufficient for assessing real-world performance.

It should be noted that the variation examined in this paper doesn't necessarily reflect real-world variation. The two-fold and three-fold increase in thermal stress on the right and left mount shroud is indeed significant. As the thermal stress of the mount shrouds is a limiting factor of product life length, a large variation of stresses implies large deviations in life length between

individual manufactured products. Such quality inconsistencies should best be avoided.

It should be noted, however, that in the CAD-model, there is no smooth edge between the mount shroud and the connecting part when the variation is significant. This concentrates the stresses on the edges. A more realistic approach would involve deforming the part to create a smooth transition, something that is done in welding. It would be desirable to predict the deformation that occurs in welding. In addition to deforming geometry, welding also changes the material properties and creates inner stresses in the materials. With recent advances in welding simulation techniques[1], it should be possible to link welding simulation to the platform. This should be investigated further, as this paper shows that the high

stresses often occur in the weld edges.

Another limit of the simulation is that the virtual assembly was done with rigid components. In reality, the components exhibit some non-rigid behavior, the effects of which remain unassessed.

Further, another difficult thing to assess is the human factor in assembly. The assembly process is not fully automated, and the experience of the factory worker plays an important role in the final results. The experienced tweaking and turning of the assembly done by hand is perhaps the hardest thing to model on a computer.

Acknowledgements

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