This article presents a strategy for the probabilistic analysis of geometric variations and their influence on the fatigue behavior of a gas turbine housing. The task is to quantify the influence of the geometric scatter onto stresses and lifetime. This can be done by estimating statistical properties and translating them into failure probabilities. The knowledge can help to adjust safety factors and the duration between maintenance actions or can improve the quality control for manufacturing tolerances.

Workflow steps
1. Measurements
The generation of the surface laser scans is the first challenge because of the housing size of 4.9 m in diameter, 13.1 m in length and 390 t in weight. Current scanning technology creates large data volumes (more than 1 GB data to store the triangulation of one 180° scan). Several scanner positions are required due to the size of the object. The photogrammetric system GOM Tridom in combination with GOM ATOS Triple Scan was used to support these measurements (Fig. 1).

The possible time to scan the turbine is limited between production and preparation of delivery. Therefore, for some turbine housings only parts of the surface could be scanned. Due to the complex shape of the geometry, also some parts are not accessible by scanning devices. Thus, the triangulation must be edited afterwards, i.e., repair meshes, delete features, fill holes, remove outliers, reduce number of triangles (see post processing in Fig. 2). The long delivery lead times also cause that only a few turbine housings could be measured within an acceptable project time. Therefore, a very small number of samples is typically available. By taking the symmetry of the geometry into account, a larger number of samples can be obtained virtually.

2. Statistical model of geometric tolerances
New random virtual geometries are created in the robustness analysis. Using optiSLang, statistical properties (e.g., distribution type, mean value, standard deviation, correlations) are typically assigned to a small set of parameters. The software uses this information to vary the input parameters according to the pre-defined scheme. The statistical properties must be obtained from the analysis of the laser scans. In this project, a random field model (“Statistical shape model”) was chosen to represent the geometric variations (Fig. 3). Here, statistical properties are associated to each point on the housing boundary. This is very different from approaches that try to find a statistical description of CAD parameters. The random field model allows a greater accuracy in the spatial distribution of the variation patterns, because it is tied to the FEM nodes and not to just a few parameters. The parameterization can be automatically obtained by an analysis of the measurements.

First, the measurements are imported to SoS by mapping the measurements (given through STL files defining the boundary) onto the surface of the undeformed FEM mesh. SoS automatically determines the geometric deviation (measured perpendicular to the surface) for each FEM node between each measurement and the reference geometry. A subsequent step is the conduction of a statistical analysis. For each FEM node, the mean deviation and the magnitude of the variation around the mean (= standard deviation) can be determined. A first indication can be derived from this analysis at which locations a large deviation from the CAD...
geometric deviations must be restricted to surface patches. Some surface parts are machined after molding, for example, holes are drilled and ground to attach other structures, such as screws. Further, some surface parts must not be varied to ensure numerical stability of the CAE model, e.g., contact boundaries. The geometric parts subject to variation are shown in Fig. 6.

3. Numerical Model

The numerical model was mainly generated in ANSYS Workbench. Here, a semi-analytic thermal model was implemented for the gas flow to be coupled with a transient thermo-mechanical model for the prediction of the spatial distribution of temperature and stresses. Subsequently, a low cycle fatigue (LCF) analysis was carried out with SIEMENS GT internal software. The 3D FEM model includes bolting contacts and a thermal transient defining the time-dependent loading conditions.

The original mechanical model for the 90° housing part consists of 840k nodes and 380k elements. The total computing time for a single design requires more than 30 GB disk space and approximately three days on a medium HPC hardware. Therefore, the run of e.g. 100 samples in a simple Design of Experiments of a robustness analysis is not feasible within project time.

To improve the time and storage demands, only one submodel was considered with remaining 240k nodes and 270k finite elements (Fig. 7). The hardware demands could be reduced to 7 GB disk space and 2 hours per sample.

4. Robustness analysis and results

The goal of the robustness analysis is to answer the following questions:

- Is there a difference in stress distribution or endurance factors between a “true” geometry and the reference geometry?
- Is there a significant influence onto stress and endurance factor if the geometric scatter is considered? How large is the influence?

The first question can be answered by transferring each measurement into the CAE model or, simply, by computing the mean geometry. The second question requires a stochastic tolerance analysis. Here, a Design of Experiments (DOE) is virtually created and evaluated. The workflow is illustrated in Fig. 8. This involves a variation of the random field parameters according to their statistical distributions.

SoS simplifies the choice by assuming uncorrelated standard-normal variables.
The results of the CAE analysis (temperature, stresses, endurance factor, etc.) can either be analyzed in optiSLang (e.g. by their maximum values) or in SoS. For this, the ANSYS RST files are reevaluated by SoS. A statistical analysis can now be conducted for the result quantities (Fig. 9/10). The stresses can be compared, for example, with critical limits for different safety levels (exceedance probabilities). Further, the location of possible critical stresses can be easily identified.

A failure probability was not analyzed in this project, because the accuracy of the statistical model is not sufficient due to the small number of measurements. Further, a sensitivity analysis can be conducted with the Field Metamodel of Optimal Prognosis (FMOP). The FMOP associates the sensitivity of the stresses or temperatures to each FEM node for the respective input parameters (Fig. 11). In this analysis, each input parameter represents a certain variation pattern. This indicates which geometric variation shape is relevant for the temperature or stress at critical locations. The result further justifies the quality criteria to geometric tolerances in production to the respective variation shapes.

**Software and methodology**

List of applied software and their particular functions:

- **optiSLang**
  - Management and automation of the workflow
  - Generation of random parameter values and DOE
  - Analyses of scalar responses
- **ANSYS**
  - Generation of the thermo-mechanical model

**SIEMENS GT**
- Low cycle fatigue solver

**Statistics on Structures**
- Statistical analyses of the measurements
- Generation of new random geometries and transfer into the CAE process
- Statistical analyses of the FEM results in 3D
- Sensitivity analysis of FEM results with FMOP in 3D

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**Sources**

“Investigation of low cycle fatigue on large gas turbine casings under consideration of geometric tolerances”, U. Lohse, B. Voss, Th. Lowitz (Siemens AG Large Gas Turbines), H. Schulze Spüntrup (ITB Dortmund), S. Wolff DYNARDO Austria; presented at the Weimar Optimization and Stochastic Days, June 1-2, 2017