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Capturing the effects of Manufacturing Uncertainty on Turbine Blade Life using Probabilistic Techniques

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Introduction

Turbine blades are critical components affecting the life and performance of an aircraft engine. These blades, when manufactured, inevitably exhibit some deviations from their designed shape due to manufacturing uncertainty. An obvious approach for capturing these deviations may appear to be taking measurements on the manufactured blades and analysing this data for any differences from the designed values. The measurement data is however clouded by measurement error which needs to be filtered out before the influence of manufacturing uncertainty can be determined.

Methodology for Segregating Measurement Error from Measurement Data

A flowchart representation of the Principal Component Analysis (PCA) and Fast Fourier Transform (FFT) based methodology proposed for segregating measurement error from the measurement dataset to capture the underlying manufacturing uncertainty is shown in Figure 1. The measurement data comprises of two datasets- 1) one-off measurements consisting of 18 ultrasonic minimum wall thickness measurements per blade taken on a randomly selected set of 1050 air-cooled IP turbine blades manufactured over a year, 2) repeated measurements consisting of the same 18 measurements repeated on a randomly selected sample of 11 blades manufactured within a week. Both datasets were made available to us by Rolls-Royce (RR) plc., Derby.

Since the repeated measurements are taken on blades manufactured within the same week, they are expected to contain negligible effects due to the manufacturing drift with time. Assuming that the measurement error is random in nature, the mean of the repeated measurements on each of the 11 blades results in the true thicknesses for these blades. These true thicknesses capture the effects of blade to blade manufacturing variation and are used further in defining thresholds for the PCA and FFT techniques. PCA and FFT help in filtering out the measurement error from one-off measurements to capture the underlying effects of manufacturing drift with time. This results in a set of 18 thickness measurements for 42 (19 from FFT + 12 from PCA + 11 mean thicknesses = 42) probable manufactured blade shapes.

In another study, coordinate measuring machines were used to measure the external aerofoil profiles of turbine blades. These aerofoils were superimposed upon one another to observe that all the external profiles almost overlapped each other. This means that the brunt of manufacturing uncertainty is borne by the internal core surface of the blades with negligible influence on the external surface. Therefore, it seems more sensible to deform only the core surface to obtain the 42 different probable shapes.

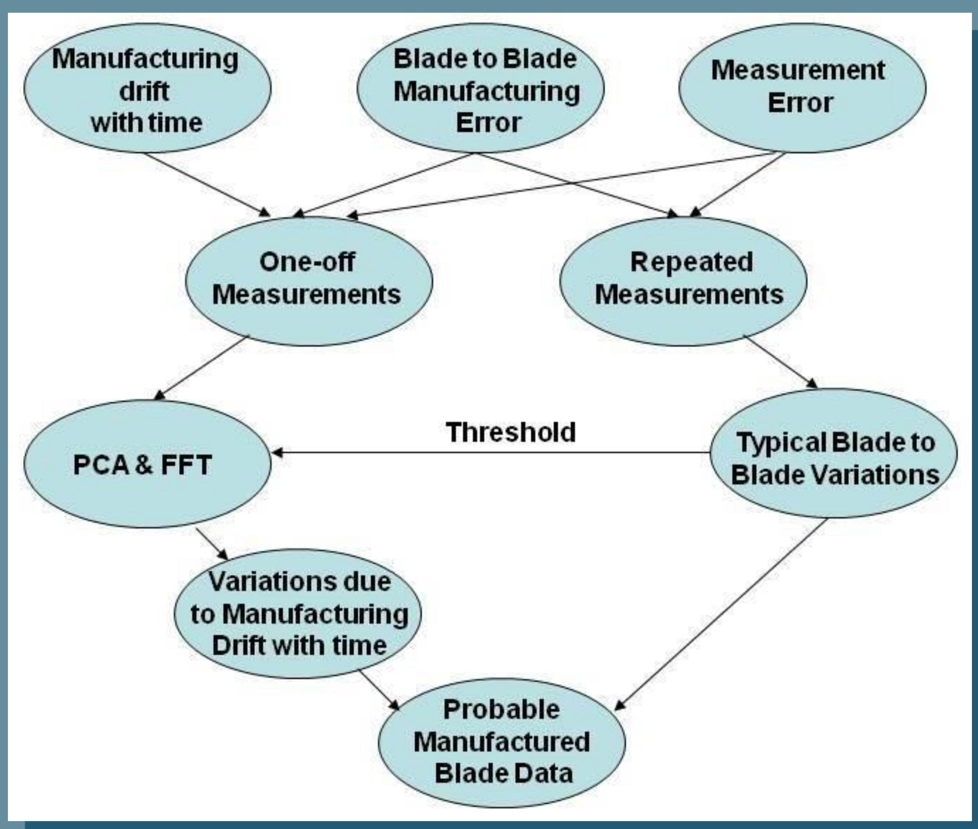

Figure 1: Flowchart representation of methodology proposed for segregating measurement error for capturing manufacturing uncertainty.

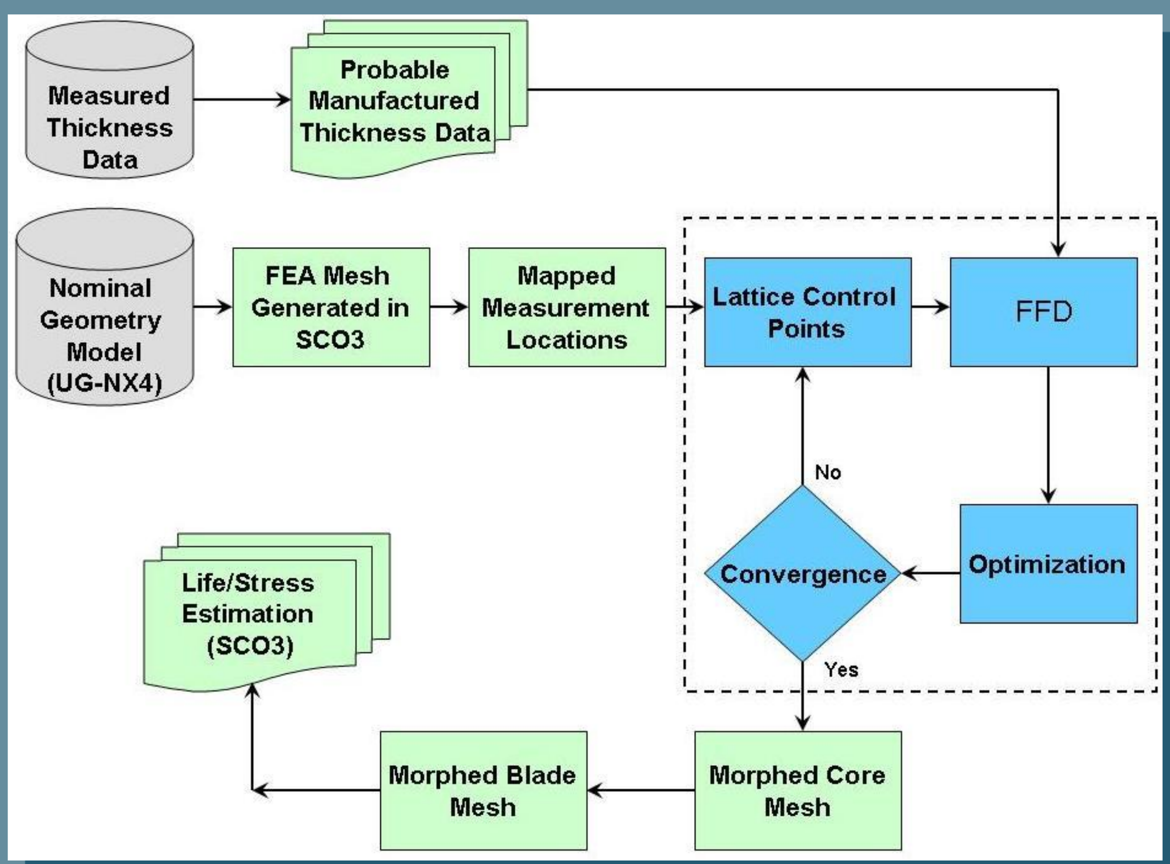

Figure 2: Flowchart representation of the methodology for turbine blade lifing analysis using FFD and SCO3 for mesh morphing.

Methodology for Generating FEA Meshes from Limited Measurements

Once thicknesses on the 42 probable blade shapes were available, the next challenge was using this limited data for generating 3-d models for the 42 blades. Free Form Deformation (FFD) is a very popular geometry manipulation technique that aids in deforming the nominal geometry to any desired shape based on limited information. The proposed FFD-based methodology applied for the present purpose is shown in Figure 2.

As shown in the flowchart, probable thickness data for the 42 blades was fed into the FFD process. The nominal model of the turbine blade in UGNX4 and a mesh on this model in SCO3 was made available to us by RR. The 18 measurement locations were mapped onto the volume mesh from the CAD model. The surface mesh of the core was then extracted from the volume mesh with the mapped measurement positions. This mesh was fed into the FFD process which worked in conjunction with a non-linear optimizer to reduce the differences between the expected and nominal thicknesses. This analysis resulted in 42 deformed core meshes. Keeping the external nodes fixed, the deformations in the core were fed as displacements into the internal core surface of the turbine blade volume mesh in SCO3 and 42 morphed meshes were obtained using the linear elasticity solving approach. These meshes were used further in SCO3 for lifing calculations.

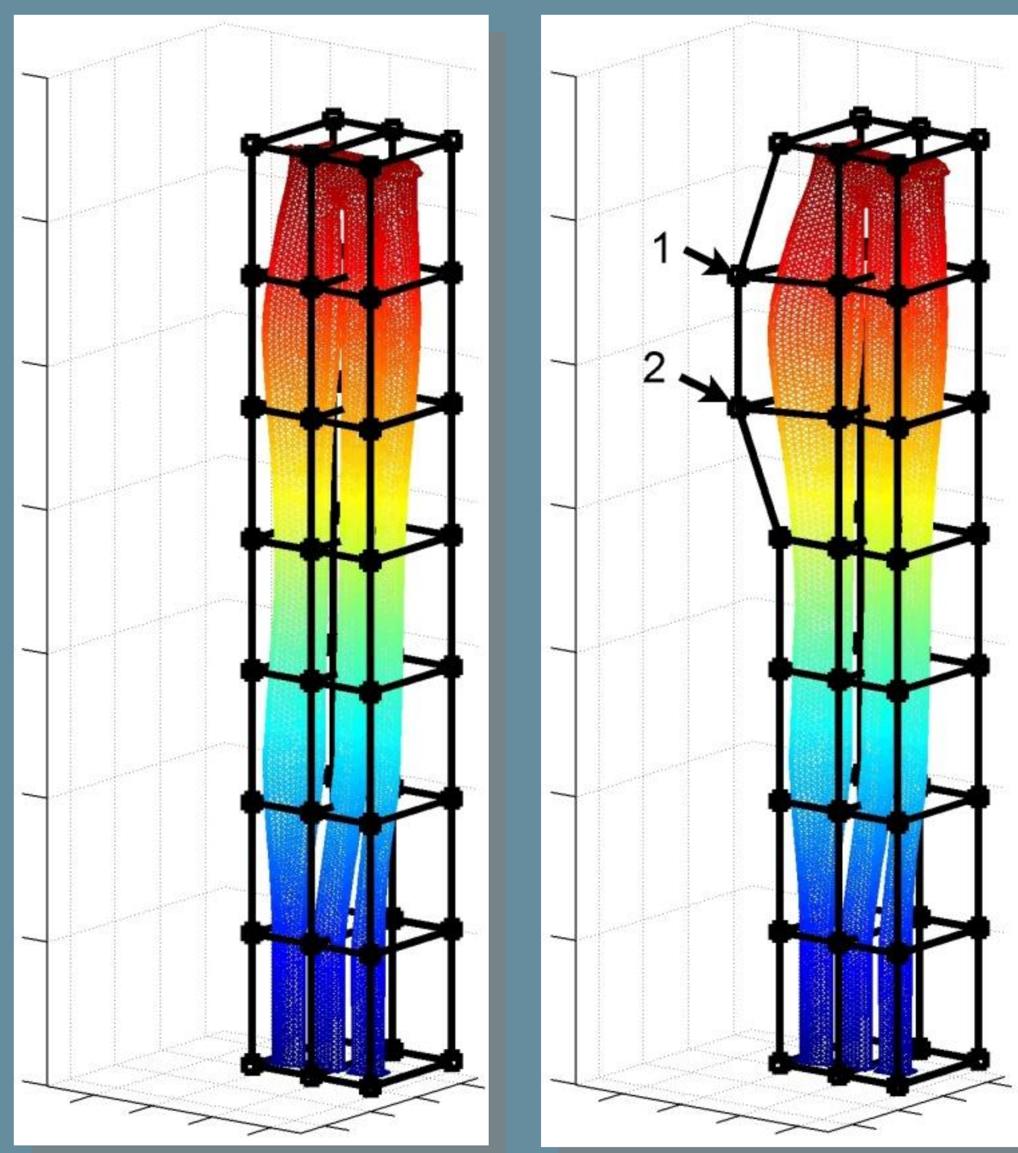

Figure 3

(a) Nominal core with no deformation

(b) Deformed core obtained from FFD when control points 1 and 2 are moved away from the core.

Free Form Deformation (FFD)

A demonstration of the application of FFD for deforming the core meshes is shown in Figure 3. Figure 3(a) shows the nominal core before it is deformed. The nominal core is enclosed in a lattice of control points that are shown as black dots connected by black lines (lattice). Movement of any of the control points deforms the core in such a way that the deformation is intuitively consistent with the motion of the control points. Figure 3(b) demonstrates an increase in the core leg thickness when control points 1 and 2 are moved away from the core.

Results

The results of the lifing analysis are shown in Figure 4. It can be observed that the mean life of the probable manufactured turbine blades shows a reduction of around 1.6% relative to the designed life with a maximum relative reduction of around 3.6% for turbine blades manufactured over a year.

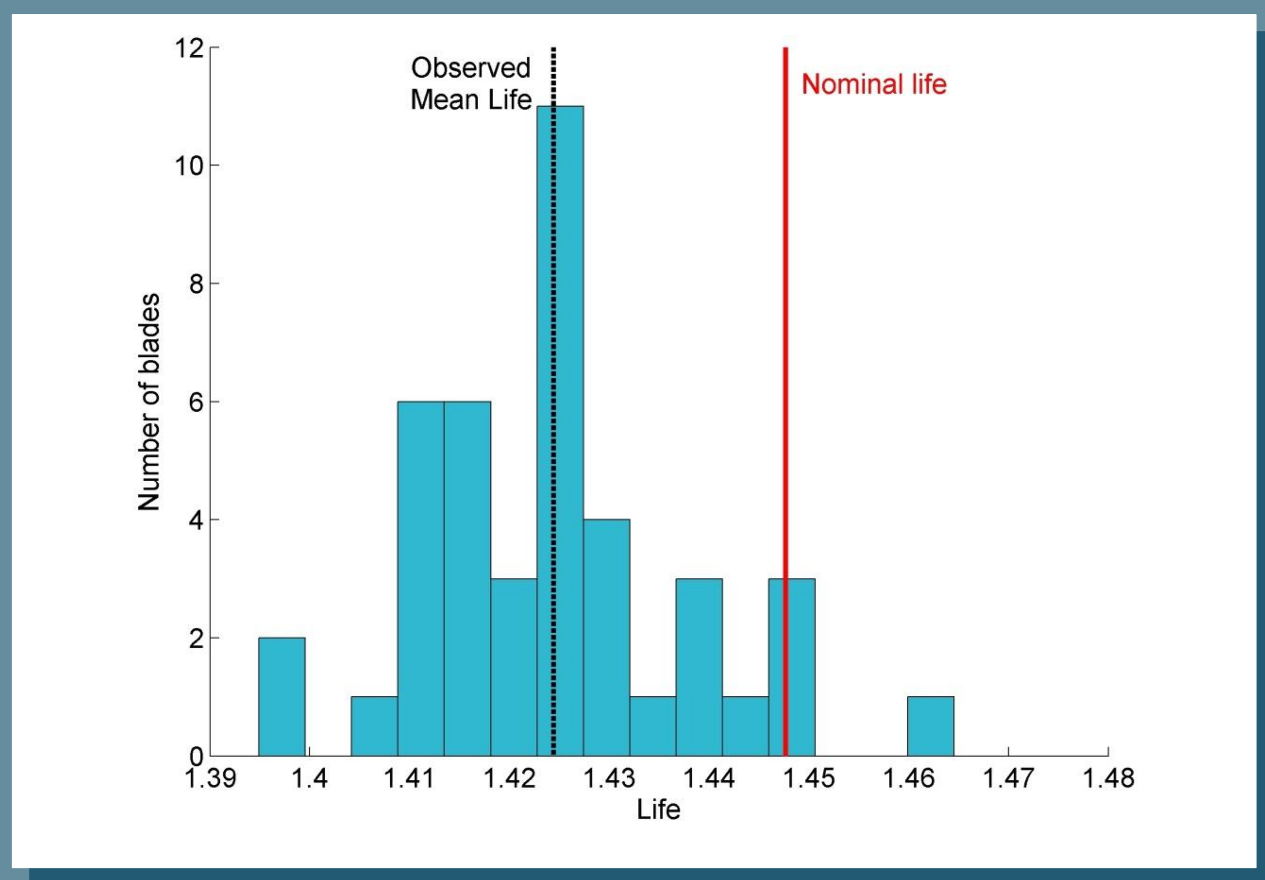

Figure 4: Histogram representing the results of the turbine blade lifing analysis.

Future Work

A workflow has been created in iSIGHT which uses a further FFD based approach for modifying the base geometry to generate new turbine blade designs which may exhibit better lifing properties. The series of revised base geometries obtained from this flow will be analysed for determining the effects of manufacturing uncertainty using the methodology described here to seek a more robust design.

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