Estimating the effect of Manufacturing Variability on Turbine Blade Life

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Abstract. The life of turbine blades is central to the integrity of an aircraft engine. Turbine blades, when manufactured, inevitably exhibit some deviations in shape from the desired design specifications due to the influence of manufacturing variability. This manufacturing variability may in turn lead to variations in the expected life and performance of these blades. It becomes important therefore to understand and model the effect of manufacturing variability on turbine blade life. The present work proposes a methodology which employs an existing geometry manipulation technique, namely Free Form Deformation (FFD), to generate 3-d models of the probable manufactured blade shapes. FFD is employed in conjunction with optimization for morphing the base geometry to generate different probable manufactured blade shapes in a case where a limited number of measurements are available per blade to characterize these differences. Lifing estimations on these perturbed geometries show that the presence of variability due to manufacturing processes may result in a reduction of around 1.6% in mean life relative to the designed life, and, a maximum relative reduction of around 3.6%, for turbine blades manufactured over a span of one year.

Keywords: Manufacturing Variability, Geometric Variability, FFD, Turbine blade, Life.

1. Introduction

Turbine blades with internal cooling passages possess some of the most complicated geometries in engineering when it comes to mesh generation and mesh morphing. Creating the turbine blade model in a standard Computer Aided Design (CAD) package by skilled professionals may take months. Moreover, the CAD models may not precisely represent the manufactured blade shapes as these are influenced by variability in the manufacturing processes. The characterization and segregation of manufacturing variability is a subject of research in itself which involves the understanding and application of various probabilistic data analysis techniques (Thakur, Keane and Nair, 2009). If datasets capturing the geometric variations caused due to the influence of manufacturing variability are available, they may be used for generating 3-d model representations of the probable manufactured blade shapes. Meshes on these perturbed geometries may then be used for finite element analysis (FEA) and lifing estimations.

The manual generation of a new model in a CAD tool for each and every probable manufactured blade shape might prove to be a very costly affair due to the large time span required and the paucity of highly skilled professionals needed for this purpose. This leads to the need to automatically morph the base/nominal

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4th International Workshop on Reliable Engineering Computing (REC 2010)
Edited by Michael Beer, Rafi L. Muhanna and Robert L. Mullen

ISBN: 978-981-08-5118-7. *Published by* Research Publishing Services.
doi:10.3850/978-981-08-5118-7_030

geometry so as to generate 3-d models representing the different blade shapes. Due to the limited number of measurements available per blade, it is very difficult to characterize the complete geometric variability exhibited by the blades coming out of the manufacturing process. It becomes essential therefore to use geometry manipulation techniques, like Free Form Deformation (FFD), which enable the use of a limited number of measurements to approximate the deformations on the entire blade surface, resulting in fair estimations of the final distorted shapes. However, the process of identifying the best match to the expected deformation requires an optimization process to be used in conjunction with FFD.

FFD was first introduced by Sederberg and Parry in 1986 (Sederberg and Parry, 1986), and later developed by Coquillart (Coquillart, 1990), Hsu, Hughes and Kaufman (Hsu, Hughes and Kaufman, 1992), Lamousin and Waggenspack (Lamousin and Waggenspack, 1994), Noble and Clapworthy (Noble and Clapworthy, 1999), and Singh and Kokkevis (Singh and Kokkevis, 2000). Recently, FFD techniques have found wide applications in aerodynamic shape parameterization and optimization problems (Désidéri and Janka, 2004; Majd, Duvigneau and Désidéri, 2006; Samareh, 2004; Sarakinos, Amoiralis and Nikolos, 2005). However, its use for characterizing geometric variability from a limited number of measurements, especially in the turbine blade manufacturing industry, remains relatively unexplored. The present work proposes a methodology which employs the Sederberg and Parry FFD technique for generating probable shapes of manufactured turbine blades from the limited data available on these blades. The deformed shapes so generated are then used for FEA analysis and lifing calculations.

The flow of this paper is such that, in Section 2, the mathematical formulation behind the Sederberg and Parry FFD technique, and the formulation of the objective function for the shape matching optimization problem are presented. This is followed by a detailed explanation in Section 3 of the proposed methodology which employs FFD for characterizing geometric variations in turbine blades due to manufacturing variability. Following this, the application of the proposed methodology to the present problem and the results obtained from the FEA study on the morphed geometries are discussed in Section 4. The paper ends in Section 5 with a brief summary of the presented work and a discussion on the scope for future work.

2. Mathematical Formulations

FFD is a very popular geometric deformation technique that allows the user to conceptually embed an object, or several objects, in a parallelopiped of clear, flexible plastic, and apply deformations to the plastic such that the embedded object is deformed in a manner that is intuitively consistent with the motion of the plastic (Sederberg and Parry, 1986; Lamousin and Waggenspack, 1994). This clear, flexible plastic is more commonly called the *lattice* of control points that encloses the object to be deformed. However, the task of obtaining the best match of the blade shape to the manufactured blade measurements cannot be executed without an optimization process working in conjunction with FFD. This is because the control points in FFD are located on the parallelopiped structure enclosing the object to be deformed, and not essentially placed on the surface of the object itself (unless the object is a cube or a cuboid). Consequently, it may not be very easy to establish a direct relationship between the displaced coordinates of the control points and the relative deformation that takes place on the surface of the object as a result of this displacement.

One may argue here that the Directly Manipulated Free Form Deformation (DMFFD) approach (Hsu, Hughes and Kaufman, 1992) may overcome this problem. However, if the lattice control points on more than one planar sections are being moved in the x and y-coordinate directions and these planes happen to be sufficiently close to each other (which is true for our case), displacement of the control point at one plane may also result in some form of relatively lesser deformation of the object at the adjacent plane, and vice-versa. This form of coupled behaviour of the deformations at various planar sections makes it extremely difficult to find a simple solution to the problem of bringing a few selected points on the surface of complex geometries to the desired coordinate positions without using some form of optimization process along with FFD.

The problem of finding the best possible match to the expected blade shape is solved by selecting the points on the base model for which measurements are available and using FFD to move the coordinates of these points to get as close as possible to their expected values. This typically represents an optimization problem where the objective is to minimize the difference between the moved coordinates and the expected coordinates. The mathematical formulations behind the FFD approach and the optimization process used for the present case are discussed as follows.

2.1. Free Form Deformation (FFD)

It should be noted that this section discusses the mathematical formulation of the FFD technique that was proposed by Sederberg and Parry in 1986 (Sederberg and Parry, 1986) and will be employed for the present problem. Before proceeding on to the mathematics behind FFD, the reader needs to be familiar with Bernstein polynomials and Bezier curves (Farin, 2002; Neuerburg, 2003).

FFD is defined in terms of a trivariate tensor product of Bernstein polynomials where the control points form the co-efficients of the polynomials. First of all, a local coordinate system is imposed upon the parallelopiped structure enclosing the object such that any point $\mathbf{X}$ has (s, t, u) coordinates in this system,

$$\mathbf{X} = \mathbf{X_0} + s\mathbf{S} + t\mathbf{T} + u\mathbf{U}, \tag{1}$$

where, $\mathbf{X_0}$ is the origin of the local coordinate system. The (s, t, u) coordinates of $\mathbf{X}$ can be found by the vector solution,

$$s = \frac{\mathbf{T} \times \mathbf{U}.(\mathbf{X} - \mathbf{X_0})}{\mathbf{T} \times \mathbf{U}.\mathbf{S}}, t = \frac{\mathbf{S} \times \mathbf{U}.(\mathbf{X} - \mathbf{X_0})}{\mathbf{S} \times \mathbf{U}.\mathbf{T}}, u = \frac{\mathbf{S} \times \mathbf{T}.(\mathbf{X} - \mathbf{X_0})}{\mathbf{S} \times \mathbf{T}.\mathbf{U}}. \tag{2}$$

It may be noted that for any point on the interior of the parallelopiped, $0 < s < 1, 0 < t < 1$ and $0 < u < 1$. Now, a grid of control points ($\mathbf{P}_{ijk}$) is imposed upon the parallelopiped structure such that it is divided into $l + 1$ planes in the $\mathbf{S}$ direction, $m + 1$ planes in the $\mathbf{T}$ direction, and $n + 1$ planes in the $\mathbf{U}$ direction. These control points need to be uniformly spaced along each direction in accordance with the expression below :

$$\mathbf{P}_{ijk} = \mathbf{X_0} + \frac{i}{l}\mathbf{S} + \frac{j}{m}\mathbf{T} + \frac{k}{n}\mathbf{U}, \quad i = 0, \cdots, l, \quad j = 0, \cdots, m, \quad k = 0, \cdots, n. \tag{3}$$

The deformation is specified by moving the control points $\mathbf{P}_{ijk}$ from their undisplaced positions to new ones. The deformation function $\mathbf{X}_{ffd}$ is defined by a trivariate tensor product Bernstein polynomial,

$$\mathbf{X}_{ffd} = \sum_{i=0}^{l} \binom{l}{i} (1-s)^{l-i} s^i \left[\sum_{j=0}^{m} \binom{m}{j} (1-t)^{m-j} t^j \left[\sum_{k=0}^{n} \binom{n}{k} (1-u)^{n-k} u^k \mathbf{P}_{ijk} \right] \right]. \tag{4}$$

Here, $\mathbf{X}_{ffd}$ is a vector containing the Cartesian coordinates of the displaced point, and $\mathbf{P}_{ijk}$ is a vector containing the Cartesian coordinates of the control points.

2.2. NON-LINEAR OPTIMIZATION

For the optimization considered here, the objective function is formulated such that,

$$Obj = \sum_{i=1}^{s} \left[(x_{d,i} - x_{e,i})^2 + (y_{d,i} - y_{e,i})^2 \right], \quad i = 1, \cdots, s, \tag{5}$$

where,

$$\begin{aligned} s &= \text{number of selected points on object (in our case, number of measurement points)}, \\ x_{d,i} &= \text{deformed x-coordinate position of the } i^{th} \text{ point}, \\ x_{e,i} &= \text{expected x-coordinate position of the } i^{th} \text{ point}, \\ y_{d,i} &= \text{deformed y-coordinate position of the } i^{th} \text{ point}, \\ y_{e,i} &= \text{expected y-coordinate position of the } i^{th} \text{ point}. \end{aligned}$$

It may be noted in equation (5) that Obj is non-linear in nature. Hence, the most obvious approach seems to be using one, or a combination of, non-linear optimization algorithms to solve the current problem. The built-in function available in MATLAB called '$fmincon$', which uses a Sequential Quadratic Programming based algorithm is employed for the present problem. '$fmincon$' attempts to find a constrained minimum of a scalar non-linear function of several variables starting at an initial estimate. This can be represented as :

$$\min_x f(x) \quad \text{such that} \quad \left\{ \begin{array}{l} A.x \leq b, \\ Aeq.x = beq, \\ lb \leq x \leq ub. \end{array} \right\} \tag{6}$$

For the present case, our aim is to minimize Obj such that the control points vary between $\pm 10mm$ from their respective nominal positions. These bounds are specified in the vectors containing the lower bounds (lb) and the upper bounds (ub). Since the present problem does not involve any other constraints, A, b, Aeq and beq can all be declared as null matrices. Therefore, expression (6) reduces to :

$$\min_x Obj \quad \text{such that} \quad lb \leq x \leq ub, \tag{7}$$

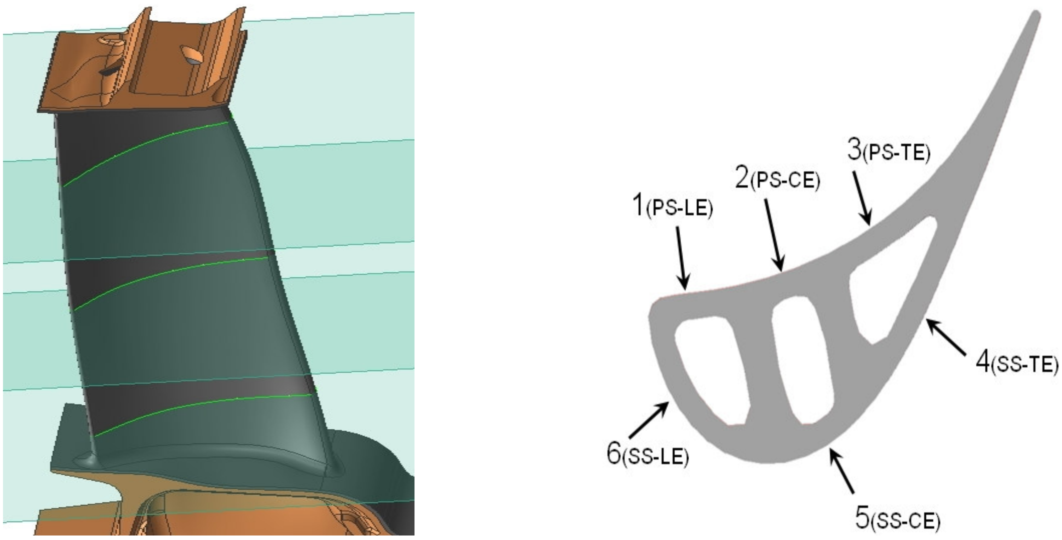
where the vector defining the nominal positions of the control points is used as an initial estimate. The final outcome is a vector of control point positions that minimizes the difference between the deformed coordinate positions and the expected coordinate positions for the selected points. The application of this set of control point movements then deforms the entire blade to its probable deformed shape.

The mathematics behind the implementation of '$fmincon$' lie beyond the scope of the present work. However for those interested, further details on this technique are available in the cited literature (Byrd, Gilbert and Nocedal, 2000; Coleman and Li, 1996; Gill, Murray and Wright, 1981).

3. Characterizing Geometric Variability from Limited Measurements using FFD

3.1. Background

Measurement data on a set of 1050 air-cooled IP turbine blades was made available to us by the Precision Casting Facility (PCF), Rolls-Royce plc., Derby. The data comprised of 18 ultrasonic minimum wall thickness measurements per blade, six each across the Tip, Mid and Root cross-sections. At each cross-section, minimum thicknesses were measured at the leading edge (LE), centre (CE) and trailing edge (TE) along the pressure (PS) and suction (SS) surfaces. Figure 1(a) shows the Tip, Mid and Root cross-sections of a typical CAD generated turbine blade model and Figure 1(b) shows the six measurements taken along each cross-section. Probabilistic data analysis techniques, namely, Principal Component Analysis (PCA)



(a) (b)

Figure 1. (a) Typical model of a manufactured turbine blade showing three cross-sections of measurement. (b) Measurement locations across typical cross-section.

and Fast Fourier Transform (FFT) analysis, were then employed to segregate the measurement error from the available measured data to capture the underlying manufacturing variability. The end result was a set of 18 minimum wall thickness measurements for 42 reconstructed blade shapes which represented the most probable values of thicknesses for the actual turbine blades manufactured on the shop floor. A detailed explanation of the referred study along with its results is discussed in the authors' previous work (Thakur, Keane and Nair, 2009).

A CAD based nominal model of the turbine blade (in Siemens NX4) and the base mesh on this model (in SC03) was provided by PCF, Rolls-Royce, Derby. NX4 is a CAD Design tool provided by Siemens Product Lifecycle Management (PLM) Software Inc. (Siemens PLM, 2009; Shih, 2006). SC03 is a Rolls-Royce proprietary automatic analysis system designed for fully integrated stress, displacement, thermal and vibration analysis through the complete design cycle (Armstrong and Edmunds, 1989; Theorem Solutions, 2005).

A separate study was conducted such that coordinate measuring machines were used to examine the outer aerofoil shapes along the Tip, Mid and Root sections for a set of randomly selected turbine blades. These aerofoil profiles were then superimposed upon each other and it was observed that the outer aerofoil shapes almost overlapped each other with negligible influence due to manufacturing variability. This implies that the brunt of manufacturing variability is mostly borne by the internal core surface of the blade. It is sensible therefore, to fix the external surface of the turbine blade model, and only deform the nominal internal core shape 42 times to generate the 42 different probable manufactured blade shapes.

3.2. Methodology

The major objective of the current problem is to use the limited number of measurements available per blade to predict the geometric variability along the entire 3-d CAD model such that these models may then be used for FEA analysis. As discussed before, FFD is one such technique that enables the deformation of an entire object/model based on the information available on a limited number of points on the surface of the model. The flexibility of the FFD process can be controlled by carefully selecting the control points that are used for deforming the base model.

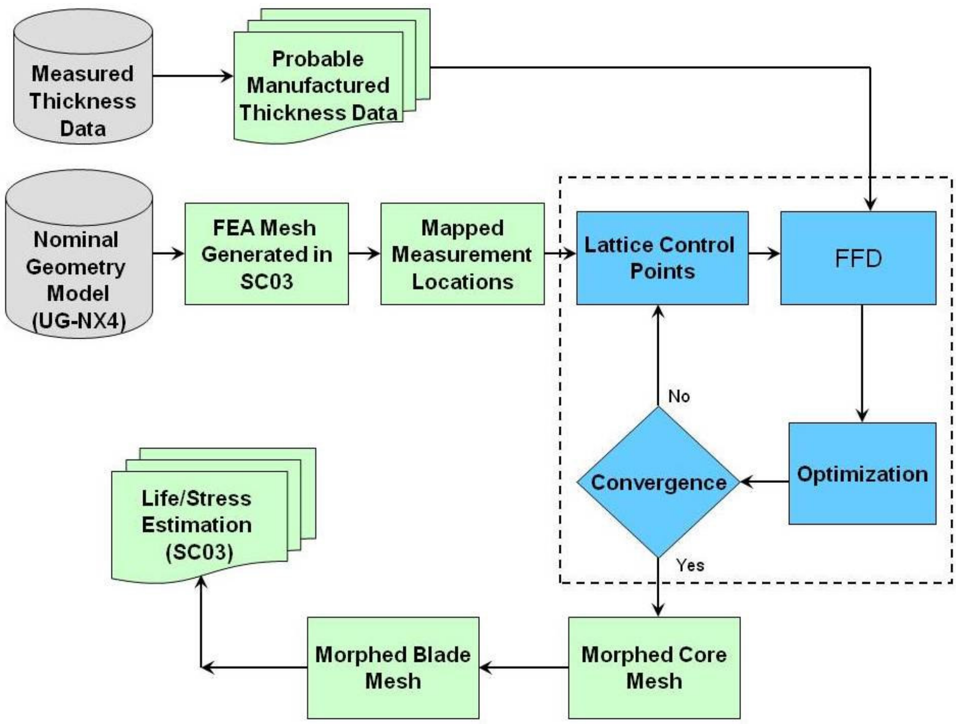


Figure 2. Flowchart representation of the methodology proposed for lifing analysis of turbine blades using FFD.