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Aerodynamic Shapes In PLM Codes
Knot Placement Optimization For Accurate Aerofoil Fitting

UTC for Computational Engineering

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Introduction

This project investigates the use of NURBS definitions for airfoil design alongside the Padram design system (SS04) and the RRD Parablading system (JA81). This involves the geometry definition running as part of the hot-to-cold SMT.

NURBS (Non-Uniform Rational B-Splines) are flexible and powerful, and can be used to represent both analytical curves and free form shapes, using a relatively small amount of data. These parametric curves and surfaces are defined by their order, a set of control points, a weight corresponding to each control point, and a knot vector for each parametric direction, which determines which segment of the curve or patch is affected by each control point. The knot vector is a sequence of increasing breakpoints along each dimension. The non-uniform aspect of NURBS refers to the fact that the knots may be different and unequally spaced.

NURBS can be used to define a curve to fit a series of existing points. These can be achieved either by interpolation, going through all the given points, or by approximation, finding the curve that will go as close as possible to all the points. Curve or surface fitting, however, requires a very good parameterization of the NURBS, and optimization techniques can be used to find the right combination of parameters that provide an accurate fit.

When fitting a point cloud with a NURBS curve or surface, the user normally adjusts the position of the control points and modifies them to reduce the error between the curve they define and the original set of points. This approach is often times sufficient to obtain accurate approximations. However, when the shapes have rapid changes in curvature, it has been found that the modification of the control points is not always sufficient to obtain an accurate fit and engineers have to increase the number of control points to improve the fit. In some cases, the number of control points necessary for an acceptable approximation is so large that the advantages of using NURBS are lost.

The effect of changing the location of the knots on the shape of the curve is not at all intuitive, nor mathematically simple. Analytical approaches are complex mathematically, and limited to modifying a few knots at a time. It is clear, therefore, that a numerical approach into the effect of knot modification on the spline shape would be easier to implement and provide more flexibility and control over the shape of the curve or surface.

Description of the software used

Parablading is an aerofoil generating tool that can be used either to generate aerofoils from scratch or to convert from point clouds into parametric models, with NURBS definition for the suction and pressure sides. It is not restricted to 2D sections but can generate and parameterize 3D blades by stacking several sections. Parablading uses a constrained and weighted least squares curve fitting algorithm. All weights are set to one and point and slope continuity are enforced as boundary conditions.

Isight is an engineering platform which provides a suite of very flexible and visual tools to create simulation workflows for process automation and design optimization. The tools include a variety of applications, including commercial software components, and internal components that can be easily modified by the user to perform certain tasks. Isight contains a number of techniques to explore the design space, such as Design of Experiments, Optimization and Approximation tools.

The optimization techniques used in the present study, the OptionsNSGA2 package developed at the University of Southampton, have been introduced into Isight in the form of a plug-in to the Optimization driver component.

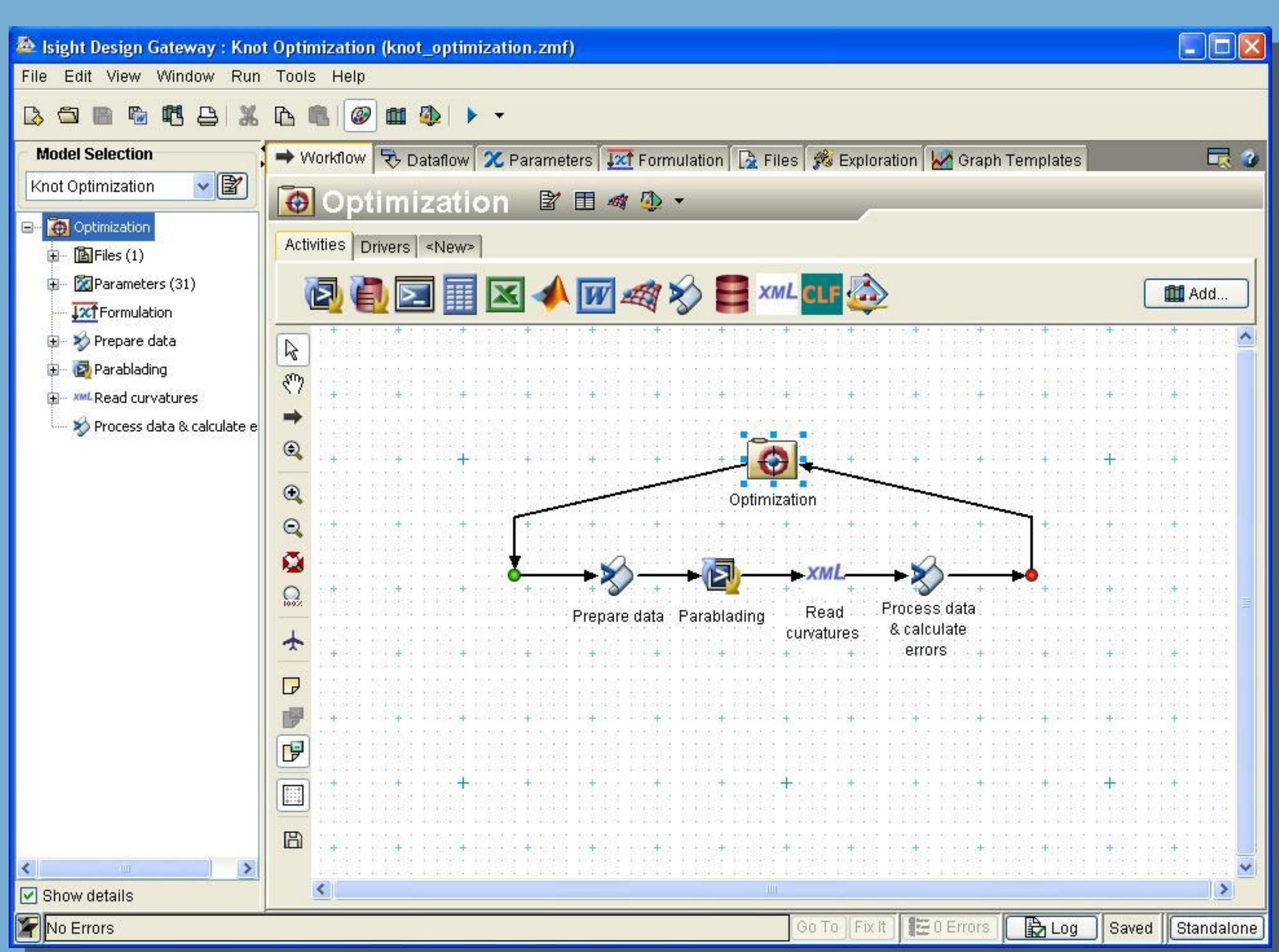

Figure 1. The Isight workflow for optimizing the NURBS knot vector using Parablading.

Results

The proposed procedure (shown in Figure 1) is to be applied to a series of Rolls-Royce aerofoils of different families to obtain a standardized approach to be used in the future for all shapes. A series of three modified NACA 65 aerofoils from the public domain are also included, and one of them is shown presently.

The first phase of this project involved the general minimization of the positional error between the original aerofoil point cloud and the fitted NURBS for shapes of particular complexity, with high curvature changes near the leading edge. For such shapes, a uniform or quasi-uniform knot distribution (with equally distributed knots), produced high oscillations in the curvature of the spline, and the number of segments (or knots, and therefore control points) had to be increased to a large value to minimize and eventually eliminate them. It was shown that by using the location of the knots as variables and the RMS error on a given section as the objective, a suitable knot vector could be obtained that would minimize the error considerably without having to add more knots. The same was also demonstrated for a 3D case and the same knot vector could be used to minimize the error in all the blade sections simultaneously.

Based on these preliminary results, a new problem specification has been defined, in which the aim of the process becomes the reduction of both the positional error and the curvature error below a pre-determined tolerance. For positional error, it is desired that the maximum error, normalized by true chord, is less than 0.004.

Figure 2 shows the Parablading NURBS fit for an aerofoil using 3rd degree NURBS, 15 control points, using an even knot distribution. The approximating spline presents very large oscillations in the curvature plot, showing that the control points alone cannot always be used effectively to produce a good approximating NURBS curve.

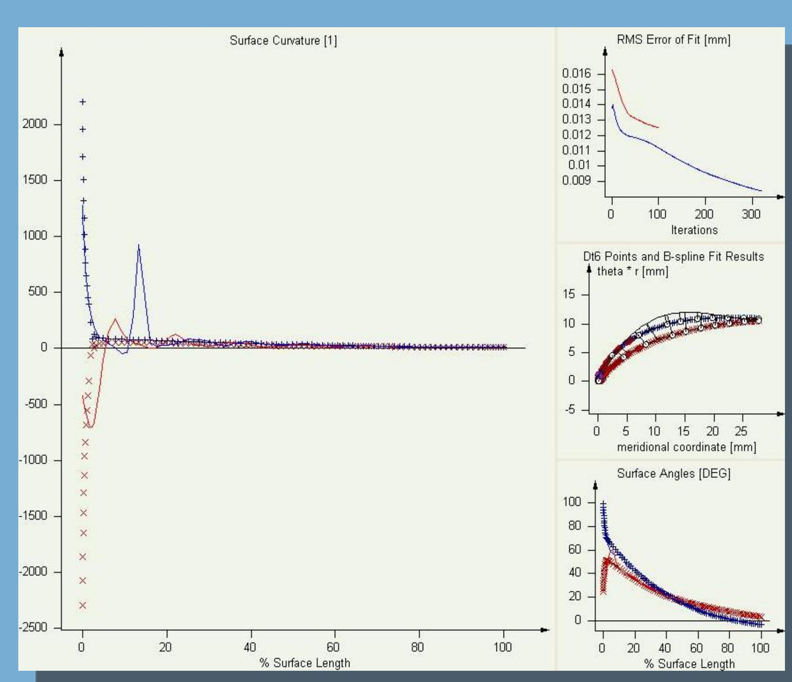

Figure 2. Parablading view of original aerofoil points and approximating NURBS with a uniform knot distribution.

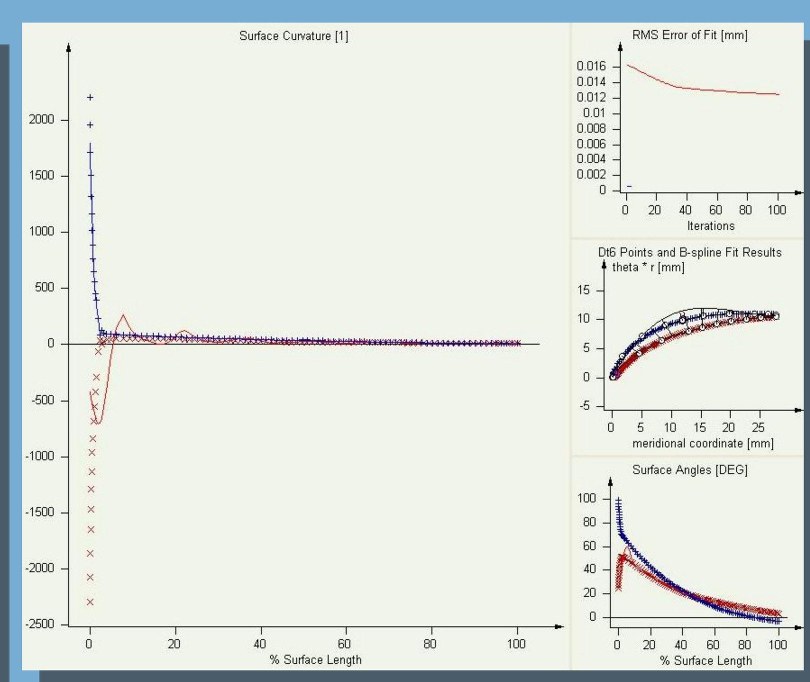

Figure 3. Parablading view of section 1 of the optimized blade (suction side only).

To address this problem, firstly a single 2D section is considered. Since the problem is to be applied to multiple objectives, genetic algorithms are used, in particular the OptionsNSGA2 method. Only one curve is considered at a time, in particular the suction side is first explored. The optimization algorithm was capable of reducing the positional error below the 4% of chord mark in 37 iterations.

When considering several sections of the blade at a time, the problem becomes truly multi-objective. This particular blade has 9 sections, so the maximum error on all 9 suction sides become the objectives and a unique knot vector must be found to satisfy the specified error requirement in all of them simultaneously. This is achieved after only 48 iterations. The optimized results are shown in Figure 3, for the first of all the 9 sections only. The knot vector that produces these results is the following:

Knots = [0 0 0 0 0.0109 0.0226 0.1103 0.2411 0.4714 0.5136 0.5236 0.8122 0.914 0.9309 0.9436 1 1 1 1]

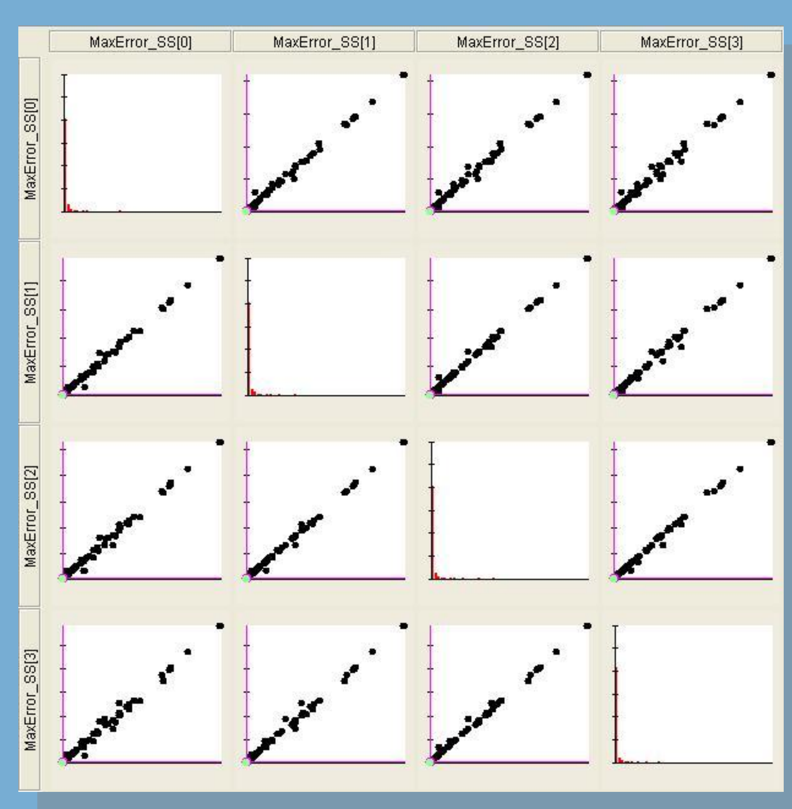

Figure 4. Pareto front of multi-objective optimization of the suction side for all sections of the blade.

More knots are placed close to the leading edge, where the curvature changes more drastically.

Figure 4 shows a partial view of the pareto front obtained for this multi-objective problem (only the maximum error of the first four sections is shown). The green point shows the best point after a full run of 25 generations and a population of 25. The pink point, however, satisfies all the positional error requirements and is obtained after only 48 iterations.

Ongoing and future work

Continuing work will include the curvature error and explore different optimization possibilities to obtain a reliable solution that can be applied to different families of aerofoils.

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