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Point-based approach to enhance the quality of geometric data for CAE applications

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Abstract

Commercial CAD surface modelling software is based almost exclusively on Bézier, B-spline and NURBS representations. These methods offer simple interactive shape modification and computationally efficient interrogations, but have some serious practical limitations. The root cause of all these problems is that the parametric polynomial methods are not geometry-based, and the trouble is compounded by the master geometry philosophy which treats the CAD model as if it were absolutely correct. An alternative purely geometric approach to surface modelling has been established, where the surface shape is characterised by a grid of points lying on the surface, but it is recognised that this approach would require major changes in existing CAE systems. This application paper explains the rationale to develop algorithms, which would plug into existing CAE software systems, so that the user could benefit from the point-based construction without disturbing the established mode of operation. The new point-based approach has achieved significant success in ensuring that form tools produce panels within a specified tolerance.

Keywords: Point-based surfaces; forming tool design.

1. Introduction

Computer Aided Engineering (CAE) is a mature technology which can create photo-realistic images of the most complex shaped components, analyse performance using Finite Element Analysis (FEA) or Computational Fluid Dynamics (CFD), manufacture tooling and control production. The technology has transformed engineering over the past thirty years but widening access and increasing expectations of accuracy and reliability are exposing fundamental weaknesses. As ever in engineering, the devil is in the detail and there is a growing awareness that high quality, virtually perfect Computer Aided Design (CAD) surfaces are a pre-requisite for successful CAE integration. Commercial CAD surface modelling software is based almost exclusively on Bézier, B-Spline and Non Uniform Rational B-Splines (NURBS) representations. These methods offer simple interactive shape modification and computationally efficient interrogations but have some serious practical limitations. In particular, it is a highly specialised and time-consuming task to define a totally satisfactory free-form CAD surface (Ball 1997), and any flaw in the definition can subsequently compromise CAD data exchange (Wilson 1998), FEA and CFD mesh generation (Farouki 1999) and manifest itself in the CNC machining paths (Klossowski 1998). The root cause of all these problems is that the parametric polynomial methods are not geometry-based, and the trouble is compounded by the master geometry philosophy which treats the CAD model as if it were absolutely correct (Ball 1997).

A purely geometric approach to surface modelling has been established (Cripps 2003), where the surface shape is characterised by a grid of points lying on the surface. The

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3 difference between a characterisation of this type and an explicit surface equation is that it
4 does not define a unique surface but rather an equivalence class of surfaces that are, within
5 tolerance, the same shape. It is relatively straightforward to specify a grid of surface points
6 and the format is equally applicable to physical objects, computer models or conceptual
7 designs. In all cases, the interpolating surface is defined by a recursive geometric
8 construction which generates a denser grid of points at each iterative stage. The distinctive
9 features are the accurate estimation of curvature from point data (Tookey and Ball 1997) and
10 the G^2 Hermite interpolation with a generalised Cornu spiral (GCS) which guarantees
11 monotonic curvature variation between data points (Ali *et al.* 1999).
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13

14 2. Geometric modelling

15 The point-based surface construction method is well established and guarantees surface
16 definitions of a very high geometric quality, and using these high quality definitions in
17 practical applications gives great benefits. However, it is recognised that the point-base form
18 is not universally accessible and hence the need to convert point-based surfaces into a more
19 accessible form. The intention was to develop a robust interface with the NURBS surfaces in
20 CATIA[®] with the expectation that the full generality of the rational form would be used to
21 define an approximation to the point-based construction. Since CATIA[®] recognises the
22 rational form only in geometric display and approximates with the non-rational form (NUBS)
23 for subsequent CAE computations, it was decided to concentrate on non-rational piecewise
24 biquintic surfaces assembled with G^2 continuity and to approach the definition as a
25 generalisation of non-rational bicubic B-spline surfaces. **This approach is applicable to any**
26 **NUBS-based CAD system.** Given a rectangular grid of points with boundary tangent
27 directions and parametric knot vectors, boundary tangent magnitudes and corner twist vectors
28 have to be determined such that the quality of the resulting interpolated spline surface is
29 comparable to the original point-based data.
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34 In terms of parameterisation, the popular approach is to assign values of the knot vector and
35 specify end tangent magnitudes so that the parameter approximates proportional distance
36 along the NUBS curve. The most commonly used distance-based scheme is chord length
37 (Farin 2001). The resulting spline will not have constant proportional arc length at the knots
38 of the NUBS, especially for unevenly spaced data sets. This could be addressed by optimising
39 for the given data to improve the length of the curve span between consecutive points and the
40 specified parameterisation. Alternatively, motivated by fitting circular and spiral arcs, a
41 mathematical construction that optimises the parameterisation for the circle is sought. The
42 idea (Cripps and Ball 2004) is to determine a parameterisation that tries to make the first and
43 second derivative at each data point orthogonal, i.e. $d^2C(u)/du^2 \cdot dC(u)/du = 0$. Thus given a
44 string of data points; \mathbf{p}_i ($i=0, \dots, 1$), let $\mathbf{a}_i = \mathbf{p}_i - \mathbf{p}_{i-1}$, $\mathbf{b}_i = \mathbf{a}_{i+1}$ and $\mathbf{c}_i = \mathbf{a}_i + \mathbf{b}_i$, then:
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$$48 \quad u_{i+1} = u_i + (u_i - u_{i-1}) \frac{\left[(\mathbf{b}_i \cdot \mathbf{c}_i)^2 + \frac{1}{2} \|\mathbf{b}_i\|^2 \|\mathbf{c}_i\|^2 \right] (\mathbf{a}_i \cdot \mathbf{c}_i)}{\left[(\mathbf{a}_i \cdot \mathbf{c}_i)^2 + \frac{1}{2} \|\mathbf{a}_i\|^2 \|\mathbf{c}_i\|^2 \right] (\mathbf{b}_i \cdot \mathbf{c}_i)} ; i=0, \dots, n-1, \quad (1)$$

49 with $u_0=0$ and $u_n=1$. The end tangent magnitudes are given by:
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$$53 \quad \frac{d\mathbf{P}(u_0)}{du} = \frac{\left[3(\mathbf{a}_0 \cdot \mathbf{t}_0) \|\mathbf{a}_0\|^2 \right] \mathbf{t}_0}{\left[2(\mathbf{a}_0 \cdot \mathbf{t}_0) + \|\mathbf{a}_0\|^2 \right] u_1 - u_0}, \quad \frac{d\mathbf{P}(u_n)}{du} = \frac{\left[3(\mathbf{a}_n \cdot \mathbf{t}_n) \|\mathbf{a}_n\|^2 \right] \mathbf{t}_n}{\left[2(\mathbf{a}_n \cdot \mathbf{t}_n) + \|\mathbf{a}_n\|^2 \right] u_n - u_{n-1}} \quad (2)$$

54 This parameterisation scheme is optimal with respect to approximating circular arcs and
55 numerical evidence has shown that the approximations match the radius of curvature profiles
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to within $\pm 5\%$. Encouragingly, the approach is suitable for both even and unevenly spaced data. For data sampled from a quality curve, the approach performs better than non-optimised chord length parameterisation and is therefore worthy of further attention since it is stable and direct, requiring no iterative methods or optimisation. As expected, it performs less well on spiral segments, but is good enough to suggest that an acceptable approximation to spiral segments can be achieved by using the orthogonal parameterised spline, raising it to quintic and adjusting the internal control points to suit (Cripps and Lockyer 2005). When interpolating a surface in CATIA[®], there is a need to 'average' the knot vectors for the respective curves in each parametric direction, but this is not an issue with an appropriate sampling of points from the point-based surfaces.

Existing methods for constructing the corner twist vectors have been evaluated and the Adini method, which simply adopts the twist vectors of a linearly blended Coons patch approximation, gave the best results (Barnhill *et al.* 1978). The quality of the Adini twist estimate was surprising because the method seemed naive. The errors in a bicubic spline approximation are typically worst in the four corner bicubic patches. In these regions, the spline surface with Adini twists gives consistently smaller errors than the linearly blended Coons patch and, assuming quadratic variations, it is possible to construct a linear combination with reduced errors. The Adini twist, when applied to all four corners of a single bicubic patch, produces a Coons patch by definition. When an Adini twist is used on the corner of a multi-patch interpolation, the resulting corner patch is not identical to a Coons patch; the non-corner twists of this sub-patch are, in general, different. For quality surfaces, there is an approximate linear relationship between the mid-point of the multi-patch surface, the mid-point of the corresponding Coons patch and the mid-point that lies on the 'true' surface. As a consequence, there is an approximate linear relationship between the corresponding twist vectors, which can be expressed in the following form for one corner (Lockyer 2007):

$${}^A\mathbf{S}_{uv}(0,0) = (1-\lambda) {}^C\mathbf{S}_{uv}(0,0) + \lambda {}^T\mathbf{S}_{uv}(0,0), \quad (3)$$

where ${}^A\mathbf{S}_{uv}(0,0)$ is the Adini twist, ${}^T\mathbf{S}_{uv}(0,0)$ the true twist, and ${}^C\mathbf{S}_{uv}(0,0)$ the twist that would cause the interpolated surface to pass through the mid point of the Coons surface.

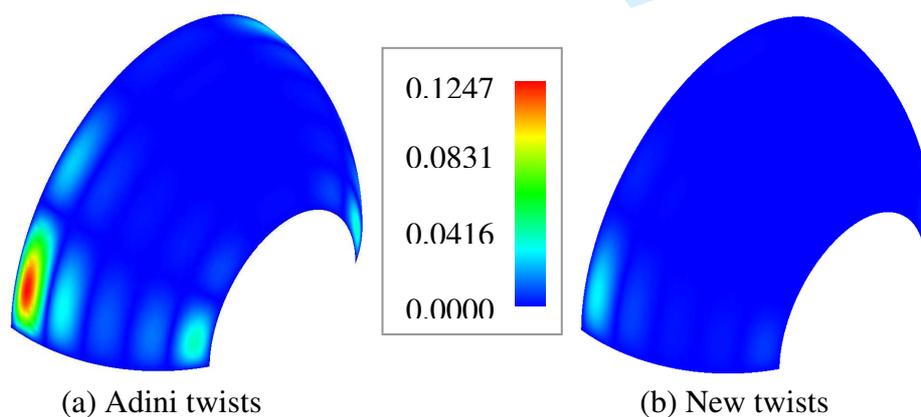


Figure 1. NUBS interpolation using Adini(a) and Improved twists(b).

By considering how the continuity conditions are affected by varying the number of patches, it is possible to generalise this process for k spans. It can be shown that: $\lim_{k \rightarrow \infty} \lambda_k = \frac{1}{2}(3\sqrt{3} - 4) \approx 0.59808$. After 4 spans, the relative error in λ_k is less than 0.01%

(Lockyer and Cripps 2005). Figure 1 shows a typical result for a surface comprising 6X6 bicubic patches. Using zero twists gives a maximum discrepancy of 0.5611 mm. This was reduced to 0.1247 mm with Adini twists and 0.0309 mm with improved twists.

The resulting NUBS interpolated surface based on average orthogonal parameterisation and improved twists minimises any disturbance to the quality of the original point-based definition. Hence the effects of the geometry on downstream processes can be effectively filtered out, enabling such processes to be studied and hence controlled more accurately. This is illustrated in the following section where the CAE application relies on the quality of the geometry to ensure acceptable results.

3. Finite element modelling and form tool design

Finite element software can be used directly to model a forming process (Lin 2003) and predict the spring-back in a formed panel, but the real engineering problem is to determine the tool shape so that the panel springs back to the required shape (Ho *et al.* 2003 and Jeunechamps *et al.* 2006). In practice it can be a time-consuming activity not only to iterate to an acceptable triangulation of the tool surface but to tidy the geometry for CNC machining. Consequently, the challenge is to automate the definition of the tool shape and, incidentally, to shift the focus of finite element modelling from analysis to design.

3.1 Tool design process

The first stage was to implement a system shell for simulating spring-back using the commercial finite element solver ABAQUS[®] for creep age forming (CAF) processes (Lin and Dean 2005), which is used, for example, to form aircraft wing panels. The point based surface definition method was incorporated, through a user defined subroutine in ABAQUS[®], with algorithms to calculate the distance of a node from a tool surface and the tangent plane at a point on the tool surface. Denoting the required panel surface by \mathbf{P} , (Figure 2), the tool surface at the n^{th} iteration by \mathbf{T}_n and the corresponding predicted panel surface by \mathbf{P}_n , the iterated tool surface is defined by: $\mathbf{T}_{n+1} = \mathbf{T}_n + (\mathbf{P} - \mathbf{P}_n)$ $n=0,1,\dots$, with $\mathbf{T}_0=0$. The iteration terminates when $\mathbf{D} = \|\mathbf{P} - \mathbf{P}_n\|$ is sufficiently small.

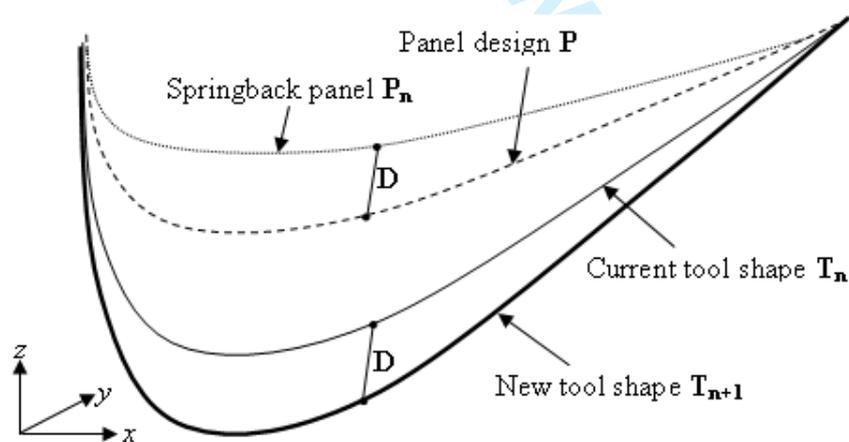


Figure 2: Illustration of offsetting the current tool surface

The methodology is generally applicable to spring-back problems but the principal interest was in creep age forming where the spring-back is high (about 70%) compared to other sheet metal forming processes.

The next stage was to construct the tool surface model. The shape quality of the tool surfaces was guaranteed by using a sparse grid of points, refined using GCS recursion. Having determined an appropriate grid for the panel surface P , it was assumed that the same number of points would be appropriate for all tool, T_n , and predicted panel, P_n , surfaces and the relative geometric spacing of the points across the respective surfaces should be the same. The effectiveness of this iteration method for tool design is directly related the accuracy of spring-back predicted via FE simulation.

3.2 Materials modelling and FE simulation

To obtain an accurate prediction of spring-back in creep-age forming, one of the most important aspects is to have an appropriate material model, which enables the creep deformation and thermally-activated stress relaxation to be accurately predicted. A group of creep ageing and stress-relaxation tests were designed and carried out for a 7XXX series aluminium alloy, which was solution heat-treated, quenched and cold-stretched. Precipitates nucleation and growth mechanisms are now understood and the effects of precipitate size on mechanical properties and creep deformation have been investigated (Figure 3).

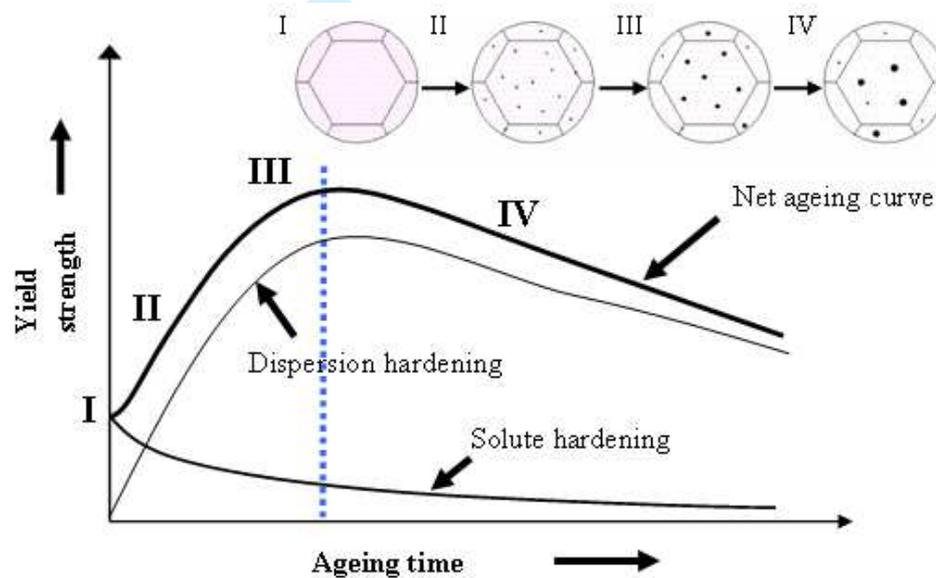


Figure 3: Schematic representation of material ageing stages: (I) Supersaturated solid solution, (II) Nucleation of GP zones (coherent) (III) Precipitate coarsening (semi-coherent) (IV) Over-aged condition (incoherent).

Based on a unified theories approach and ageing kinetics, and assuming isothermal ageing and particle growth at constant volume fraction, a new set of physically-based, unified ageing-creep constitutive equations has been proposed. This material model characterises precipitate formation and growth under the creep ageing condition and their interaction on creep (Ho *et al.* 2004). The unified ageing-creep constitutive equations are solved using an implicit numerical integration method and the time step for the integration is automatically controlled. This ensures that the creep curves can be accurately computed. The equations were determined from creep-ageing experimental data using Evolutionary Programming (EP)-based optimisation methods (Li *et al.* (2002)) which aims to minimise the fitness function: the sum of the squares of the shortest distances between the computed and experimental data. The procedures to calculate the shortest distance of an experimental data

point to the corresponding numerically integrated creep curve were detailed by Ho *et al.* (2004).

The creep deformation of the aluminium sheets in creep age-forming is governed by the determined unified creep-ageing constitutive equations, which were implemented into ABAQUS[®]. In addition to the original constitutive model, the gradients, $\partial\Delta p/\partial p$ and $\partial\Delta p/\partial\sigma_c$ were determined accurately, so that the step time could be controlled efficiently through the implicit integration algorithm within ABAQUS[®]. Multi-step numerical procedures have been developed to simulate the creep forming process and to evaluate the spring-back using ABAQUS[®]. The procedures for the simulation of spring-back in creep age forming were detailed by Lin *et al.* (2006).

3.3 An integrated approach

The point-based approach to tool design using FE analysis within the design process can be summarised by the following stages:

- Tool surface modelled using a commercial CAD package, for example CATIA[®].
- Point-based model constructed using the geometric modelling plug-in.
- Point-based model taken as the input to the FE solver, for example ABAQUS[®].
- Iterations within the FE solver alters the tool shape to compensate for springback.
- Resulting point-based tool surface placed back in host CAD system via the geometric modelling plug-in.

The integrated numerical procedure for (a) predicting age hardening and spring-back via FE simulation and (b) offsetting the tool shape to compensate for the spring-back has been applied in a case study and shown to converge with the errors approximately halving at each iterative stage. Tool offsetting is carried out via an application software package developed through the research. The new trial tool is defined using the point based method and implemented into ABAQUS[®]. Typically, 5 iterations of FE analysis are required to enable the tool shape to be determined to enable the difference between the designed and predicted panels to be controlled within a specified tolerance.

4. Conclusion

The major premise in this paper is that commercial CAD surface modelling software, based on Bézier, B-spline and NURBS representations, offer many advantages to the user, but have intrinsic serious practical limitations. The root cause of all these problems is that the parametric polynomial methods are not geometry-based, and the trouble is compounded by the master geometry philosophy which treats the CAD model as if it were absolutely correct. The alternative point-based surface modelling approach creates high quality surfaces that can be used in CAE applications without these practical limitations, but the authors recognise that the major CAD vendors are unlikely to change their valuable software code. The ability to represent the point-based reference in NURBS format delivers the point-based method to existing CAD packages. The CAE application shows that the point-based methodology has considerable potential, and that commercial reluctance to change can be overcome with this approach. Future work includes an investigation of direct modelling using the point-based approach, consideration of the applicability of a point-based approach to solid modelling and, finally, a more robust plug-in to interface with other FE solvers.

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