A hybrid surface fitting module for analysis in the Python Contour Method software

Z. Cai[1,2a] and M. J. Roy[1,2]

[1]Department of Mechanical and Aerospace Engineering, The University of Manchester, Manchester M13 9PL, UK;

[2]Henry Royce Institute, The University of Manchester, Manchester M13 9PL, UK

[a] zhe.cai@manchester.ac.uk

Abstract. The contour method is a destructive technique used to determine residual stresses typically in metallic components. After 25 years of use, its significance has been well acknowledged. Open-source software (pyCM – the Python Contour Method) for the analysis component of the method has been developed to widen its use and harmonize results. However, it has been found that surface fitting with a bivariate spline can be less effective when representing complex measured out-of-plane displacement data. This work aims to develop a robust surface model to process contour method surface deflection measurements that may contain localised errors or require more spatial resolution in specific regions. This has been realized by employing a two-step surface fitting model, upgrading the single-step bivariate surface fitting module currently implemented. It will be demonstrated that such an approach can adequately maintain a high fitting resolution while achieving a desired level of data smoothing elsewhere.

Key words

Residual stress; Contour method; Data processing; Surface fitting.

Possible Sessions

Residual stresses; Novel experimental techniques

Introduction

The contour method(CM) [1] for residual stress determination is novel in terms of destructive techniques in that it returns a complete stress component acting orthogonal to a cutting plane of interest. The deformation of this plane during a relaxing cut is measured and converted into boundary conditions for a linear elastic finite element (FE) analysis, and the stresses on the cut plane are reconstructed according to superposition theory. An analytical model is usually fitted to the data before the FE analysis, a process known as surface fitting. This is to smooth out spurious points that may be present and allow the boundary condition to be queried at arbitrary locations [2] to match the FE mesh.

Currently, the best practice [3] is to employ bivariate spline fitting to produce a surface model composed of piecewise functions known as knots, offering high flexibility to take advantage of the higher spatial resolution achieved with laser surface scanning techniques [4]. Such a model was integrated into an open-source reconstruction package, the Python Contour Method (pyCM)[5], to promote wider dissemination of the CM and facilitate a repeatable approach. However, there are limitations to this model as the interval it can do so is based on uniformly spaced knots, which control the fitting resolution: larger knot spacing results in greater smoothing but lower fitting resolution. This, therefore, limits the fitting frequency to the largest irregularity that needs to be smoothed within the dataset.

To address this, a hybrid surface fit is proposed, involving a two-step process that enables more precise representation in selected regions while maintaining a high level of smoothing in less weighted areas, which are either noisy or contain cutting irregularities that can be challenging in conventional one-step fitting.

Methodology

The hybrid surface fitting module introduced in this study serves as an upgrade to the surface fitting module of pyCM. In the standard fitting package in pyCM, the user can assign the knot spacing to control the length of each spline, and the order of fit that determines the flexibility of each spline, in both *x* and *y* directions. The upgraded fitting package enables a two-step fitting process, comprising a primary fit and a secondary fit, where the residual from the primary fit is fitted with finer-spaced splines for local improvement. A bivariate polynominal function is implemented in the primary fitting, controlling a single, contineous function to approximate the global trending of the overall dataset. Although it is less flexible compared to the bivariate splines used in the secondary fit, it allows extrapolation beyond the edge, enabling erroneous data to be removed initially and extrapolated back later.

The overall fitted surface can be represented as

$$z(x,y) = \begin{cases} f_{primary}(x,y) + f_{secondary}(x,y) & (x,y) \in secondary\ area \\ f_{primary}(x,y) & (x,y) \notin secondary\ area \end{cases} \quad (1)$$

However, since distinct boundaries exist between the primary and secondary areas, sharp discontinuities are observed on the blended surface at the junctions. To address this, it is necessary to apply a blending function near the boundaries by assigning a weighting from 0 to 1. An illustration of this process in a 2D view is provided in Fig. 1

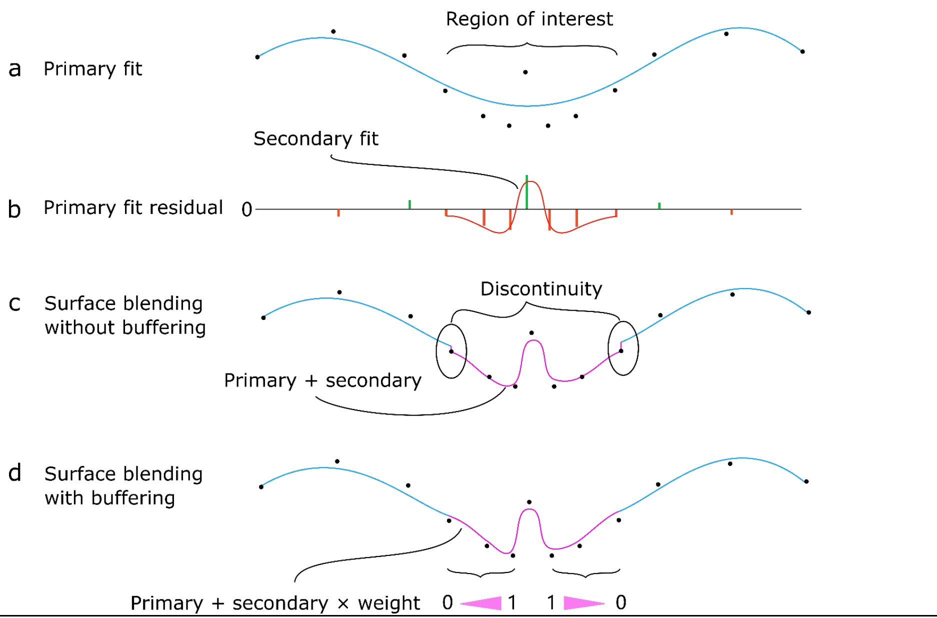

Fig. 1 An illustration of hybrid surface in a 2D domain showing a (a) primary function fitted to a dataset with a large knot spacing resulting a higher fitting residual at (b) region of interest, where the secondary function will be applied. The (c) blending of two surface functions will introduce discontinuity that can be mitigated by (d) multiplying a weight function to the secondary fit adjacent to the boundaries.

Conclusion

The hybrid fitting approach effectively addresses local irregularities in the data, such as those caused by accidental cutting interruptions, by selectively applying a primary surface function of higher smoothing globally, while finer details are captured using a secondary fitting function. When data trimming or extrapolation near the edge is necessary, the extrapolated regions with higher uncertainty from the primary fit are also subsequently underweighted. This development can significantly improve the contour method's application for residual stress analysis.

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