euspen's 24th International Conference & Exhibition, Dublin, IE, June 2024
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Investigation of the filtering effect of virtual image correlation methods in the context of ISO standards

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Abstract

Geometrical metrology involves capturing large data sets (point clouds, images, voxels, etc.). From these, pertinent information is extracted. When using imaging sensors and Computed Tomography (CT), a key step is Contour Identification, i.e., the identification of the transition between the workpiece and its surroundings. While several methods can be used for contour identification, most rely on thresholding techniques, but alternative methodologies like Virtual Image Correlation (VIC) are being increasingly studied.
This work investigates two VIC methods, focusing on filtration effects embedded in the mathematical definition of the virtual contours. The two methods are based on mode decomposition and B-spline parametric curves. The analysis was conducted on images representing cross-sections of additively manufactured lattice structures. A relation between the curve parameters and the cut-off frequency f_c, as defined in standards, has been proved to be effective. This gives new prospects for implementing emerging methods in relation to filtration as defined in ISO GPS standards and additive manufacturing parts verification.

Additive Manufacturing, Lattice structure, Virtual Image Correlation, ISO GPS standards, Filtration, B-spline, Mode decomposition

1. Introduction

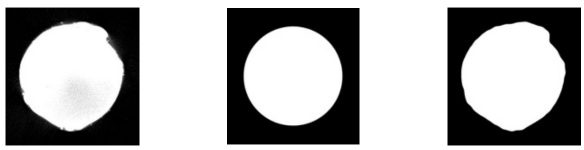
Geometrical Product Specifications and Verification (GPS) standards have been developed over the years to ensure consistent methods to perform feature operations, from design to production up to verification, adapting to diverse functional requirements. Additive Manufacturing (AM), especially in complex design geometries such as lattice structures (LS), introduces new engineering challenges for GPS. Traditional contact measuring systems are impractical for part verification, leading to the use of computed tomography (CT) and other non-destructive measuring technologies for quality control. CT generates voxel-based data, whose values are linked to the density of each point in the scanned volume, requiring contour identification for reconstructing the object's surface. Most methods rely on thresholding [1] (e.g., ISO50%), but new algorithms are being developed exploiting Virtual Image Correlation (VIC) strategies [2][3].
Virtual Image Correlation is a boundary detection process based on creating a virtual image defined by a mathematical parametric equation that will then be deformed to best represent its real counterpart. The deformation is guided by the minimisation of a score function that compares the virtual and the actual images (*Fig. 1*):

$$\{\lambda\} = \arg_{\{\lambda\}} \min \Phi(u) \qquad (Eq.\ 1)$$

$\{\lambda\}$ is the vector of values displacement for each parameter that defines the mathematical contour. The correlation score function, denoted as $\Phi(u)$ in *Eq.1*, is derived by summing the squared differences between corresponding pixels in the virtual and real images across the entire image. A displacement field $u(X)$ is applied to the virtual image g. The optimal value of $\{\lambda\}$ is computed to obtain the deformation field $u(X)$ that minimise the correlation score function Φ.

$$\Phi = \iint_{ROI} [f(X) - g(X + u(X)]^2 \, dxdy \qquad (Eq.\ 2)$$

For this work, two VIC methods have been investigated. The first, V2C, developed by De Pastre et al. [3], relies on the modal decomposition of the mathematical contour, i.e., the contour is described as the sum of different vibration modes applied to a circle. The second one, DBACD, part of a work still in progress, describes the contour using a B-spline parametric curve. The working principle is the same as the V2C, but in this case, instead of iteratively changing the amplitude of different modes, the algorithm computes a set of (x,y) displacements for each of the b-spline control points.



(a) (b) (c)

Figure 1. De Pastre et. al [3], Illustration of 2D VIC method applied to a vertical 90° strut: CT measurement image (a), initial virtual shape (b) and correlated final virtual shape (c)

This study focuses on contour analyses of a cylinder section of a lattice structure strut. The evaluation of circular profiles is described in the ISO standards 12181-1/2 [4, 5], to establish the series of operations required. Point filtration is one key step.

In the case of a CT-scanned LS, the contour points of the strut section are extracted with the $ISO_{50\%}$ method. These sections are characterised by geometrically more complex defects if compared with traditionally manufactured cylinders (the relative size of the defects is greater, and in some cases, undercuts may be detected). Therefore, applying standard algorithms to filter and separate the roughness and waviness profile components is difficult.

This work aims to investigate this *filtration effect* embedded in the mathematical parametrization of the virtual contours and see if there is any relationship between those parameters and the cut-off frequency f_c as defined in ISO 16610-21:2011 [6].

2. Material and Methods

The numerical experiment performed for this research consists of a comparison between the filtered contour according to ISO 16610-21:2011 [6] with the one obtained with the two VIC methods. The contours are extracted from a CT section of a Laser Powder Bed Fusion (LPBF) additively manufactured vertical cylinder, used in previous works [2], with 0.6 mm radii and 5 mm length and produced on an Addup FormUp 350 machine using Inconel 718 powder.

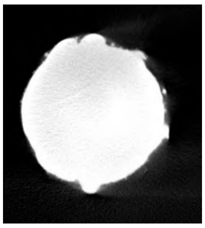


Figure 2. CT measurement section of 90° strut: 0.6 mm in radii and 5 mm in length

The image (*Fig. 2)*, extracted from a Computed Tomography volumetric scan, is first analysed with $ISO_{50\%}$ to detect its contour. The (x, y) coordinates from the extracted contour are then processed to remove the undercuts and fulfil the requirement for applying an ISO 16610-21 Gaussian filter. The image is also analysed with the two VIC methods.

The three contours ($ISO_{50\%}$+gaussian, VIC mode and VIC B-spline) are then compared with filtering parameters according to *Eq.3*:

$$f_c = \frac{n_m - 3}{2} = \frac{n_{cp}}{2} \qquad (Eq.\ 3)$$

with n_m number of modes used for V2C and n_{cp} number of control points used to define the B-spline.

This comparison has been run with different values of $f_c = [5\ 15\ 50]$ undulation per revolution (upr).

3. Results and Conclusions

In this section, the output of this numerical experiment is reported. In *Fig. 3-4-5, it* is possible to highlight the visual contour comparison for each filtering technique. One can immediately appreciate how the three filtered closed profiles are similar in the representation of geometrical defects, and especially how local differences tend to decrease progressively with increasing f_c. Further investigation could be carried out by testing different cut-off frequencies and sections; quantitative deviation could be plotted. In addition, roundness values could be computed and compared along the different f_c between the three filtration methods. Thanks to the relation described in *Eq. 3*, it becomes feasible to employ VIC methods for extracting contours filtered at a specific f_c, even in the presence of geometries that would typically hinder the use of standard methods. Deviations can subsequently be calculated as the distance between the raw data and the smoothed contour, enabling the extraction of roughness information. This could provide insights for the development/update of GPS standards applied to lattice structures and, more generally, to additive manufacturing parts.

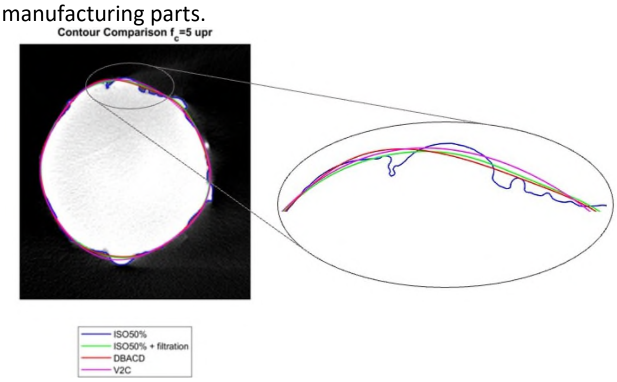


Figure 3. Contour comparison between $ISO_{50\%}$ (blue), $ISO_{50\%}$ + Gaussian filtration (green), DBACD (red) and V2C (magenta) - $f_c = 5\ upr$

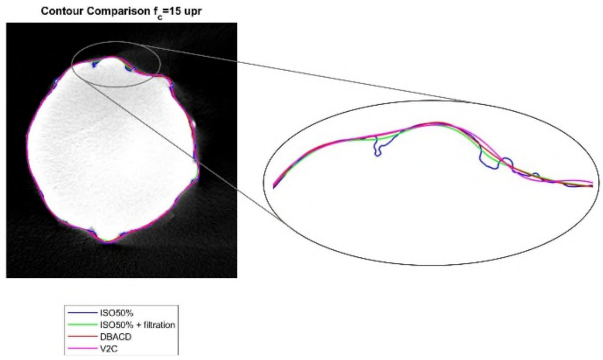


Figure 4. Contour comparison between $ISO_{50\%}$ (blue), $ISO_{50\%}$ + Gaussian filtration (green), DBACD (red) and V2C (magenta) - $f_c = 15\ upr$

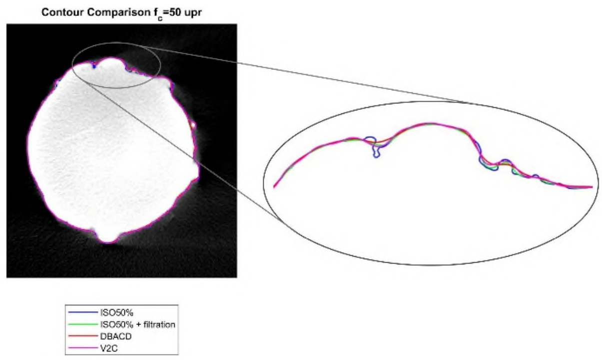


Figure 5. Contour comparison between $ISO_{50\%}$ (blue), $ISO_{50\%}$ + Gaussian filtration (green), DBACD (red) and V2C (magenta) - $f_c = 50\ upr$

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