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ANALYSIS OF GEOMETRIC TOLERANCES WITH INTEGRATION OF DEVIATIONS RESULTING FROM ADDITIVE MANUFACTURING (FDM): CASE OF PARALLELISM OF A PLANE SURFACE

This study offers an updated overview of existing approaches used to model geometric deviations in additive manufacturing. It also proposes a new framework for representing part deviations by discretizing an ideal planar surface and accounting for both deterministic and stochastic sources of variation. Deterministic deviations are described through two main components: surface waviness and overall orientation. In contrast, stochastic deviations are introduced through automatically generated variations following a normal probability distribution. The second section of this work presents a numerical investigation of a prismatic component featuring a functional planar surface produced using the Fused Deposition Modeling (FDM) technique. As an initial step, a reference specimen is fabricated to verify essential parameters associated with the mathematical models used for the FDM process. The geometric deviation model relies on converting the nominal planar surface into a mesh of nodes, after which a deformed surface—representing the actual manufactured geometry is generated using the deviations computed by the proposed approach. Finally, a Monte Carlo analysis is performed to examine how these geometric variations influence the evaluation of surface parallelism tolerance. To support interpretation of the results, a correlation is established between the simulated deviations, the specified tolerance limits, and the resulting non conformity rate calculated for each tolerance range.

1. INTRODUCTION

Additive manufacturing (AM), often known as 3D printing has undergone fast expansion across various industrial sectors due to its capability to fabricate complex components with high flexibility and reduced production costs compared to traditional manufacturing routes. Although AM provides several advantages, it can also generate

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unintended geometric defects–including waviness, cracks, and other surface irregularities–that may negatively influence the final quality and functional performance of printed parts.

In addition to its production-related benefits, AM significantly broadens the possibilities in product development by allowing designers to realize highly detailed and tailored shapes that were once challenging or even impossible to produce using conventional fabrication techniques. This versatility stimulates innovation and increases the range of achievable applications.

Ensuring stable and reliable quality in additive manufacturing remains a major challenge, as geometric imperfections can significantly degrade product functionality. Addressing these issues requires in-depth investigation to identify their origins and define appropriate mitigation strategies. Such efforts rely on a thorough examination of process conditions, material behaviour, and their combined effects, together with the use of numerical modeling tools and advanced quality assessment techniques.

This study proposes a mathematical framework for characterizing geometric deviations generated during additive manufacturing. The approach is complemented by a numerical implementation based on the developed algorithm, which illustrates the different stages of the proposed methodology.

The model focuses on the dominant categories of geometric defects: the waviness mode and the orientation mode of the nominal planar surface, both corresponding to systematic deviations. A supplementary mode capturing random fluctuations is also incorporated into the formulation.

To validate and illustrate the method, a computational analysis is performed on a prismatic part produced from polylactic acid (PLA) using an additive manufacturing system based on the Fused Deposition Modeling (FDM) process.

The main purpose of this research is to estimate the geometric deviations that can arise on a planar surface and to examine how these deviations influence the assessment of parallelism tolerance through an extensive Monte Carlo simulation.

The outline of this paper is structured as follows: first, a review of relevant literature is provided; then, the proposed approach for modeling geometric deviations based on defect modes is introduced, along with the mathematical formulation of each mode. A numerical investigation is subsequently presented to demonstrate the application of the method, followed by discussion and interpretation of the results.

2. LITERATURE REVIEW

Modeling geometric deviations remains one of the fundamental challenges in additive manufacturing (AM), as these variations can significantly influence dimensional precision, functional performance, and the long term durability of printed components. For this reason, the ability to predict, understand, and mitigate such deviations is essential for ensuring consistent part quality and for supporting the broader industrial adoption of AM technologies.

In AM processes, geometric deviation generally refers to the discrepancy between the nominal surface defined in the digital design and the actual surface produced during fabrication. Several mechanisms contribute to these differences, including discretization inaccuracies introduced during the CAD to STL conversion, thermally driven effects such as shrinkage or warping, and mechanical inconsistencies occurring during material deposition. These sources of error have been emphasized in multiple recent investigations [1–3], all of which note that the layer by layer nature of AM tends to amplify these phenomena compared with conventional manufacturing methods.

Over time, a wide range of modeling strategies has been explored to address these challenges. Early studies introduced simplified surrogate surfaces to approximate real geometries without explicitly representing local shape defects [4]. A major advancement came with the development of the skin model surface concept, originally introduced by Ballu and Mathieu and later expanded and formalized by Schleich and collaborators [6].

Another line of research investigates geometric defects through mathematical decomposition. Qiao et al. proposed a curvilinear reference framework tailored for non ideal cylindrical surfaces [7], while other studies used polynomial representations or discrete cosine transforms to express form errors as modal components [8, 9]. Similar principles appear in the work of Samper and Formosa, who applied natural vibration modes to generate compact mathematical descriptions of complex deviations [10].

This modal reasoning was later extended to tolerance and assembly analysis. A substantial body of work demonstrated how geometric imperfections propagate through assemblies and influence tolerance accumulation [11, 12]. In a complementary contribution, Chahbouni broadened this framework to integrate both deterministic and statistical tolerance approaches [13].

Within additive manufacturing specifically, several studies have aimed to better characterize deviations emerging from the layer wise deposition process. Predictive models linking geometric variations to process parameters and part design were proposed in [14, 15]. Zhu introduced a data driven strategy based on statistical shape analysis using measured point cloud data [16]. More recently, El Qemary and collaborators developed a design stage prediction method aligned with design for additive manufacturing principles, enabling early anticipation and compensation of deviations [3]. Despite these advances, many existing models remain too complex for direct industrial integration. The approach presented in this study therefore seeks to provide a simplified yet representative model, particularly suited for describing planar geometric deviations in FDM components during early design phases and tolerance evaluation.

Recent literature increasingly stresses the importance of predicting the gap between nominal and manufactured geometries early in the design process. A comprehensive review identifies three dominant deviation sources in AM: mesh related artifacts in STL files, thermally driven distortion during deposition, and machine specific mechanical inaccuracies [17]. To address these effects, hybrid thermo mechanical modeling and toolpath optimization approaches have been proposed [18], alongside machine learning based statistical prediction frameworks [19]. Additional contributions include modal decomposition approaches for cylindrical geometries [20], analytical surface deviation mapping tailored to FDM conditions [21], and adaptive geometric modeling of build orientation dependent deviation patterns [22]. Complementary studies have also examined anisotropy and surface roughness origins in FDM processes [23, 24].

The objective of the present work is to develop a structured and computationally oriented methodology for predicting geometric deviations in additively manufactured parts. The proposed model relies on deviation modes specifically associated with characteristic FDM mechanisms. The methodology begins with an experimental characterization conducted on a dedicated test artifact to identify the parameters influencing the deviation model. A numerical study on a planar surface is then performed to validate the mathematical formulation.

Two main outcomes arise from this approach:

- The methodology is implemented through an algorithm that automates deviation field computation and facilitates graphical interpretation.
- The model can be integrated into large scale production simulations to assess global performance and quantify the impact of stochastic deviations on the final surface geometry.

3. MODELING GEOMETRIC DEVIATION IN ADDITIVE MANUFACTURING

3.1. METHOD FOR DESCRIBING GEOMETRIC DEVIATIONS

A nominal surface can be described as a collection of discrete nodes, where geometric deviations correspond to the displacements applied to these nodes according to predefined defect modes.

To illustrate, take the case of a planar surface: the ideal geometry is first defined as a mesh of discrete points. The actual manufactured surface is then generated by modifying the positions of these nodes based on a combination of defect modes that arise from the characteristics of the additive manufacturing process, particularly the Fused Deposition Modeling (FDM) technique.

In our study, the planar surface is defined in the (x, y) plane at a height Z = 0, as we are only interested in the surface orientation. To represent deviations caused by the FDM process, each node with coordinates (x_i, y_j) is associated with a deviation represented by the height $Z_{i,j}$.

A plane surface is represented by the following discretized model:

$$Z_{i,j} = Z_{i,j}^{1} + Z_{i,j}^{2} + Z_{i,j}^{3} \tag{1}$$

$Z_{i,j}$: total deviations of node (x_i, y_j)
$Z_{i,j}^{1}$: deviation due to global surface orientation mode for node (x_i, y_j)
$Z_{i,j}^{2}$: deviation due to the waviness mode (x_i, y_j)
$Z_{i,j}^{3}$: deviation due to random mode (x_i, y_j)

The following Fig. 1 illustrates the representation of a plane surface discretized in grid form. The difference between the nominal and the manufactured surfaces is expressed as the accumulation of the deviation components generated by the various defect modes at each node of the surface.

By combining all these deviation contributions, the resulting surface geometry can be reconstructed. This reconstructed geometry is commonly referred to as the skin model surface. The proposed approach does not aim to establish a cause-and-effect relationship between FDM process parameters and the geometric deviations obtained on the surface. This modeling is based on a general framework for classifying defects observed on FDM-produced surfaces in the form of generic defect modes, each mode of which can have multiple causes.

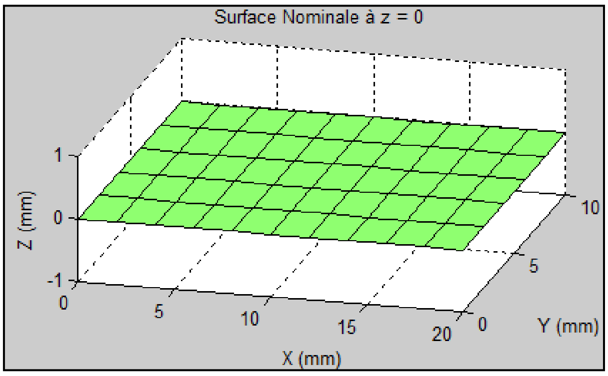

Fig. 1. A discretized planar surface

This representation method allows for a simple yet effective description of surface deviations, regardless of their specific physical origin. In this approach, the chosen defect modes: global surface orientation, surface waviness, and random deviations are not directly linked to process parameters but are representative components of the geometric deviations of surfaces resulting from FDM additive manufacturing. This simple and modular representation can be used in the analysis or evaluation of tolerances, with the goal of predicting the shape of the resulting surfaces.

Furthermore, the influence of the toolpath is an important factor affecting geometric defects, but it is not directly modeled in this study. A linear deposition configuration is considered to facilitate the interpretation of the results. This simplicity does not limit the proposed approach but provides a basis for a more general approach in future work. This approach, based on defect modes observed on the surface remaining independent, can be extended to different toolpaths.

3.2. SOURCE MODES OF GEOMETRIC DEFECTS

3.2.1. SURFACE ORIENTATION MODE

The global orientation mode represents angular misalignment affecting the top surface of the prismatic element. These orientation defects may result from several factors, including the printing direction (along the *x*- or *y*-axis) and anisotropic shrinkage effects in the *x*/*y* plane.

This mode can be described using the equation of a plane, where only the orientation is considered, its absolute position is disregarded. The deviation introduced by this mode is expressed as follows:

$$Z_{i,j}^{1} = a.x_i + b.y_j \tag{2}$$

- $Z_{i,j}^{1}$: Deviation due to global surface orientation mode for node (x_i, y_j).

The parameters a and b represent the slopes along the x and y directions, respectively. Based on the orientation angles r_x and r_y (in radians) a and b can be expressed as follows:

$$a = \tan\left(r_y\right) et \quad b = \tan\left(r_x\right) \tag{3}$$

- r_x : surface rotation in direction x,
- r_y : surface rotation in direction y.

For small rotations, it is possible to approximate tan (r_y) by r_y and tan (r_x) by r_x. The equation becomes:

$$Z_{i,j}^{1} = r_y.x_i + r_x.y_j \tag{4}$$

According to the literature, the rotations r_x and r_γ can be expressed in terms of small inclinations γ_x and γ_γ, which characterize the orientation defect of the FDM process, in rad /mm [23].

$$\begin{Bmatrix} r_x = \gamma_x.x \\ r_y = \gamma_y.y \end{Bmatrix} \tag{5}$$

- γ_x and γ_y: Small angular rotations in rad/mm,
- x et y: surface dimensions along x et y in mm.

The overall surface orientation is introduced to represent the overall inclination of the flat surface relative to the material deposition plane (x, y). This simplified representation incorporates the observed macroscopic orientation effects while preserving the model's simplicity. However, the effect of the fabricated surface orientation relative to the material deposition direction is not explicitly taken into account but implicitly.

3.2.2. WAVINESS MODE

The studied part is a prismatic rectangular component with a height of 10 mm, manufactured using an Ultimaker FDM (Fused Deposition Modeling) machine. The part is built layer by layer along the z-axis, while the nozzle moves primarily along the x-axis during material deposition.

Given this configuration, the waviness defect mode is introduced along the x-direction, as it corresponds to the principal direction of material deposition. This defect mode arises from several factors, including the cyclic motion of the nozzle along the x-axis, which induces periodic oscillations, as well as mechanical vibrations inherent to the printing process.

To model this behavior, a sinusoidal function is used, with parameters determined from measurements obtained on a printed test part. The waviness mode is expressed by the following equation:

$$Z_{i,j}^{2} = \mathrm{A1}.\sin(\frac{2\pi.x_i}{\lambda_x}) \tag{6}$$

- $Z_{i,j}^{2}$: deviation due to the waviness mode at node (x_i, y_j),
- A1: amplitude of the waviness,
- λ_x : waviness period,
- x_i: coordinate of node i according to x axis.

The parameters A1 and λ_x can be experimentally estimated based on measurements from the test part. In the present study, the investigated planar surface corresponds to a top surface manufactured with a toolpath predominantly aligned with the x-axis. This configuration is typical for the last deposited layers in FDM processes, where raster trajectories are often oriented in a single dominant direction. Under this assumption, the waviness mode is modeled along the *x*-direction. However, the proposed formulation is not restricted to this specific orientation. For arbitrary toolpath directions, the waviness mode can be generalized by defining the surface undulations along the local deposition direction, expressed as a linear combination of the *x* and y coordinates. This generalization allows the model to be extended to surfaces manufactured with inclined, rotated, or multi-directional toolpaths

3.2.3. RANDOM DEVIATION MODE

Random deviations in parts manufactured using FDM are modeled using a centred normal distribution with a mean of zero and a standard deviation, denoted as σ. The value of σ can be estimated based on data reported in the literature [24].

The random geometric deviation for each discretized point can be expressed as follows:

$$\mathrm{Z}_{\mathrm{i,j}}^{3} = \sigma \cdot \mathrm{N}(0{,}1) \tag{7}$$

With: $\mathrm{N}(0{,}1)$ is a centred normal distribution.

3.3. METHODOLOGY FOR MODELING GEOMETRIC DEVIATIONS

To support the development of this work, it is assumed that the geometric deviations observed on parts produced by additive manufacturing can be described using three principal defect modes: the global orientation mode of the surface, the waviness mode, and the random deviation mode. These modes collectively generate the geometric variations that influence the top planar surface of the component. Based on this framework, the present study concentrates specifically on this upper surface.

<u>Modeling Steps.</u>

- The nominal flat surface is first broken down into a grid of discrete nodes defined by their coordinates (x_i, y_i).
- The actual surface with deviations is represented by the values $Z_{i,j}$ at each node, calculated from the proposed mathematical model which integrates the following defect modes: orientation mode, waviness mode, and random mode.

- A 3D graphical representation of the surface is generated from the calculated $Z_{i,j}$ values

3.4. CASE STUDY: PRISMATIC PART WITH RECTANGULAR FLAT SURFACE

In this case study, a prismatic part with a flat functional surface was chosen to facilitate the verification of model parameters before moving on to cases with complex geometries. The methodology for modeling geometric deviations remains robust and standard, but the choice of methods for defect description may vary depending on the geometry of the surface under study (cylindrical or flat). This study is considered a methodological foundation for the classification and description of defects resulting from additive manufacturing.

This study is carried out on a small part, in order to guarantee a high resolution of surface defects. However, the ultimate objective of this study is the analysis of geometric tolerances, which requires a high precision in characterizing the defects.

3.4.1. GEMOTRIC DATA AND MANUFACTURING OF THE ELEMENT

This study focuses on a prismatic part with a rectangular functional flat surface, made of polylactic acid (PLA). The Fig. 2 shows the component under study. The part is prismatic with dimensions of (20 × 10 × 10) mm. The superior flat surface is tolerance for parallelism relative to the base surface of the part. The objective of this study is to model the geometric deviations of the upper surface of the part based on the proposed mathematical model.

The surface with deviations is represented by a set of nodes displaced along the z-axis from the nominal surface. In order to verify certain parameters and validate the modeling assumptions, a rectangular prismatic part with dimensions (20×10×10) mm was manufactured using PLA material on an FDM ULTIMAKER machine.

The part was designed using CATIA software, then converted into an STL file, and finally sent to the machine for manufacturing. The Fig.3. below shows the machine used to manufacture the part.

<u>Manufacturing Parameters:</u>

- Layer thickness: 0.1 mm,
- Printing speed: 100 mm/s,
- Travel speed: 120 mm/s,
- Infill density: 25%.

The Fig. 4 below shows the CAD model and the manufactured element.

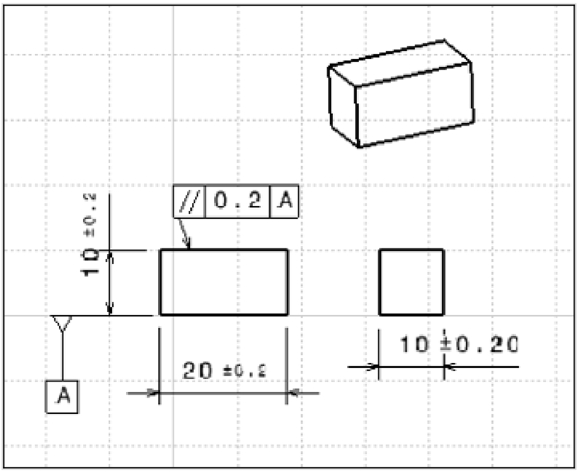

Fig. 2. Drawing of the element

Fig. 3. The ULTIMAKER FDM machine

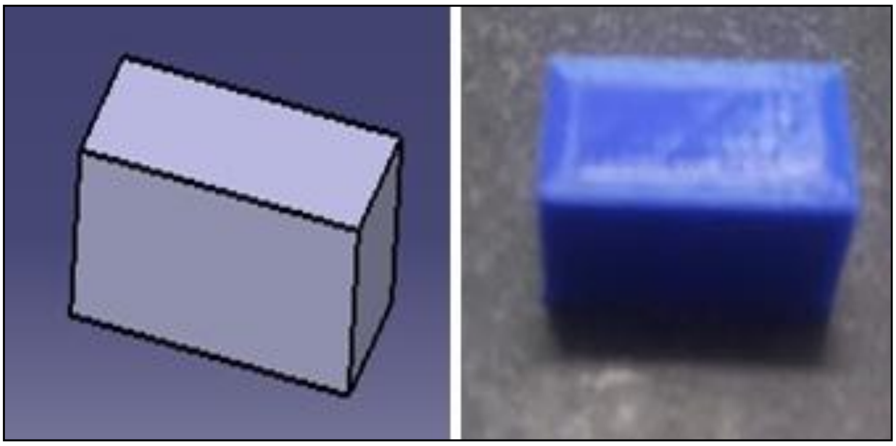

Fig. 4. Manufactured element.

3.4.2. DETERMINATION OF MATHEMATICAL MODEL PARAMETERS

Parameters $A1$ and λ_x

The parameter $A1$ represents the amplitude of the sinusoidal undulation considered on the planar surface. This parameter was experimentally estimated based on surface profile measurements taken from the test part using a Mitutoyo profilometer. The profilometer traces the surface profile along the x-axis, enabling precise evaluation of periodic undulations caused by the FDM process.

The Fig. 5 shows the measurement device used.

Fig .5. Mitutoyo profilometer

The parameter A1 is estimated at 0.05 mm based on the traced profile. The parameter λ_x which represents the wavelength of the surface undulations was estimated by counting the number of peaks over the total length of 20 mm, and then dividing this length by the number of peaks. Based on this simple method, λ_x was estimated to be 1 mm. The Fig. 6 shows the surface profile recorded by the profilometer.

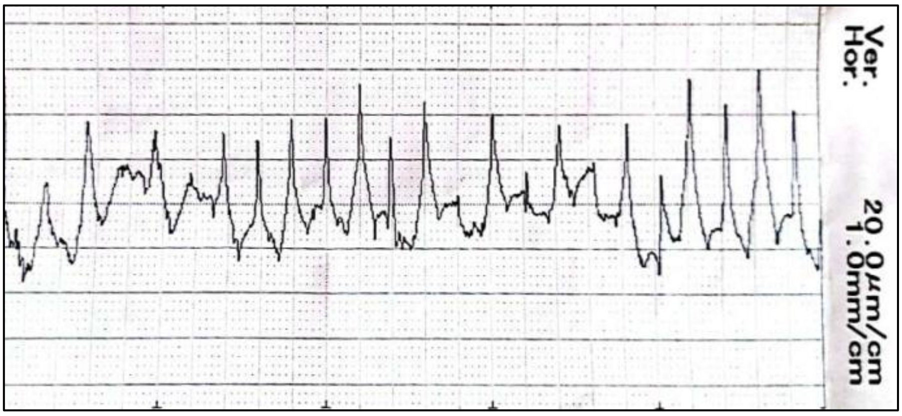

Fig. 6. Measured surface profile of the component

Parameters γ_x, γ_y and σ

According to the literature, the small inclination coefficients γx and γy, which characterize the orientation defects in the FDM process and are expressed in rad/mm, are estimated to be equal to 0.003 rad/mm [23]. The parameter σ represents the standard deviation of the random variation and is taken as the tolerance interval divided by 6, estimated to be 0.033 mm.

3.4.3. SURFACE GENERATION ALGORITHM WITH DEVIATIONS

The discretization parameters Nx and Ny were selected in order to ensure a sufficient spatial resolution for capturing the dominant geometric deviation modes while maintaining a reasonable computational cost. For the studied planar surface of dimensions 20 mm × 10 mm, the adopted grid ($N_x = 11$, $N_y = 6$) corresponds to an average spacing of approximately 2 mm in both directions, which is consistent with the characteristic wavelength of the waviness mode identified experimentally. A sensitivity analysis was performed by increasing the grid density and it was observed that the estimated surface rotations and the resulting non conformity rate remained stable beyond this discretization. Consequently, the selected sampling resolution was considered sufficient for the purposes of the present Monte Carlo analysis. The following is the algorithm for generating surfaces with deviations.

Start

Initialize:

- $Lx = 20$;
- $Ly = 10$;
- $\lambda_x = 1$;

- $Nx = 11$;
- $Ny = 6$;
- $H = 10$
- $\gamma x = 0.003$
- $\gamma y = 0.003$
- $\sigma = 0.033$
- $A1 = 0.05$

Generate a regular 2D grid $(x_i, y_j)$of size $Nx*Ny$ covering the surface.

Calculate the heights Zi,j according to the following mathematical model

$$Z_{i,j} = r_x.x_i + r_y.y_j + A1.sin(\frac{2\pi.x_i}{\lambda_x}) + \sigma \cdot N(0,1)$$

Represent the surface $Z(xi, yj)$ in 3D with a perspective view.

End algorithm

3.4.4. GRAPHICAL REPRESENTATION OF THE SURFACE

The following surface is obtained by taking into account the different types of geometric deviations: systematic and random. Figure 7 illustrates the skin model of the studied planar surface, representing the actual surface with deviations based on the proposed mathematical model. The geometric variation of this surface can be compared with an acceptable tolerance zone.

This approach allows us to predict the morphology of surfaces obtained by additive manufacturing, specifically the FDM process studied in this work, based on the modes describing deviations, which are reinforced by parameterizing the mathematical model through tests and measurements performed on the actual test part. This makes the model more robust and well-suited to the process of analysing the operating tolerances of products produced by FDM.

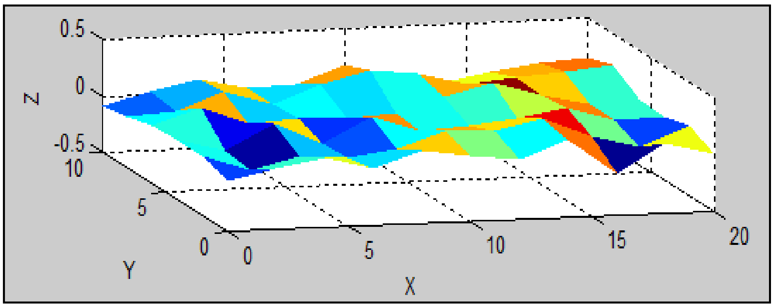

Fig. 7. The planar surface with deviations

3.5. PARALLELISM TOLERANCE ANALYSIS WITH MONTE CARLO SIMULATION

3.5.1. METHODOLOGY

The objective of the Monte Carlo simulation is to analyse the impact of deviations caused by additive manufacturing on the compliance with the parallelism tolerance of the superior surface of the part with respect to its base surface.

This approach first consists of generating a large number of rectangular planar surfaces with deviations based on the proposed mathematical model, while varying the value of the random deviation following a normal distribution.

For each generated surface, the rotations *rx* and *ry* are calculated using the least squares method.

These calculated rotations are then used to check compliance with the parallelism tolerance based on the domain method explained in [11].

According to the domain method, to satisfy a parallelism tolerance of to, the following inequalities must be fulfilled:

$$\left\{\begin{matrix} -to \leq A.r_y + B.r_x \ \leq to \\ -to \leq A.r_y - B.r_x \ \leq to \end{matrix}\right\} \tag{8}$$

With:

- A: the length of the surface, which in our case is 20 mm,
- B: the width of the surface, which in our case is 10 mm,
- rx: rotation of the surface with respect to the x-axis,
- ry: rotation of the surface with respect to the y-axis,
- to: the parallelism tolerance indicated on the part drawing.

The Monte Carlo simulation was performed for 10000 generated parts using numerical data and a custom MATLAB script. To clearly illustrate tolerance verification, a non-conformity rate (NCR) was calculated.

3.5.2. MONTE CARLO SIMULATION ALGORITHM

```
Start
Initialize data:
• Lx = 20, Ly = 10
• $\lambda_x$= 1
• Nx = 11
• Ny = 6
• H = 10
• $\gamma_x$ = 0.003
• $\gamma_y$= 0.003
• $\sigma$ = 0.033
• A1 = 0.05
• N = 10000
• to = 0.2
Generate a regular 2D grid $(x_i, y_j)$of size Nx*Ny covering the surface.
For i ranging from 1 to 10000
```

Generate surface *i* with defaults by calculating the heights *Z* (*xi*, *yi*) of surface *i* according to the following mathematical model:

$$Z_{i,j} = r_x . x_i + r_y . y_j + \mathrm{A1}. sin(\frac{2\pi . x_i}{\lambda_x}) + \sigma \cdot N(0,1)$$

- Estimation of the (average) substitution surface using the least-squares method
- Calculation of tilt angles *rx* and *ry* for each surface
- Checking conformity
- Calculate the 4 tolerance conditions according to the formulas:

✓ *C1*: 20**rx* + 10**ry* ≤ to
✓ *C2*: 20* *rx* + 10* *ry* ≥ -to
✓ *C3*: 20* *rx* - 10* *ry* ≤ to
✓ *C4*: 20* *rx* - 10* *ry* ≥ -to

If all conditions true: surface conforms, otherwise non-conforming.
Calculating the Non-Compliance Rate (NCR)
Count how many surfaces are out of tolerance.
- Calculate:

NCR= (number of non-conformities) / *N*
Store values for surface rotations *rxi* and *ryi*
Graphically represent the tolerance zone in the (*rx*, *ry*) plane, the zone limits by segments and each compliant part with a point (*rxi*, *ryi*) in blue and the non-compliant part in red.
End for
End algorithm

3.5.3. GRAPHICAL VISUALIZATION OF THE FINDINGS

The following diagram (Fig. 8) represents the parallelism tolerance zone in the (r_x, r_y) plane according to the domain method, as well as the conforming and non-conforming parts.

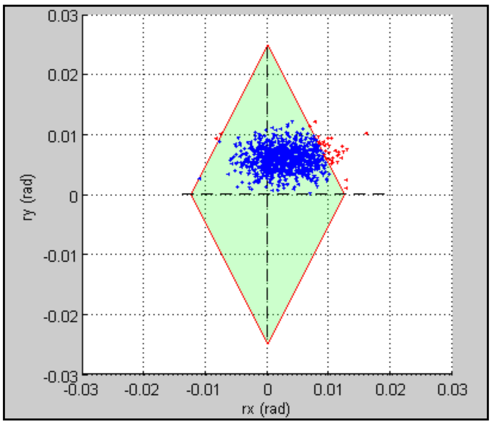

Fig. 8. Monte Carlo simulation of 10000 parts

This figure shows a graph illustrating the Monte Carlo simulation of 10000 parts with geometric deviations, and the verification of parallelism tolerance acceptance conditions.

The edges represent the limits of the tolerance zone, the blue points are accepted parts, and the red points are rejected parts. A non-conformity rate was calculated based on a parallelism tolerance of 0.25, giving 3.8%.

3.5.4. INFLUENCE OF TOLERANCE VARIATION ON THE NON-CONFORMITY RATE

Several simulations were carried out using MATLAB by varying the value of the parallelism tolerance to observe the impact of this variation on the non-conformity rate (NCR). The following Table 1 presents the obtained results.

Table 1: Variation of the non-conformity rate (NCR) as a function of parallelism tolerance (t_0)

Parallelism tolerance t_0 (mm)	Non- conformity rate NCR (%)	Parallelism tolerance t_0 (mm)	Non- conformity rate NCR (%)
0.2	14.6	0.28	1.3
0.21	12.3	0.29	0.9
0.22	9.9	0.3	0.8
0.23	6.5	0.31	0.4
0.24	5.9	0.32	0.2
0.25	3.8	0.33	0.1
0.26	2.8	0.34	0.05
0.27	2	0.35	0

The following diagram (Fig. 9) shows the variation of the Non-Conformity Rate (NCR) as a function of the parallelism tolerance. It can be observed that as the tolerance increases, the non-conformity rate decreases. This study makes it possible to establish a relationship between the geometric deviations resulting from additive manufacturing and the specific tolerance indicated by the designer.

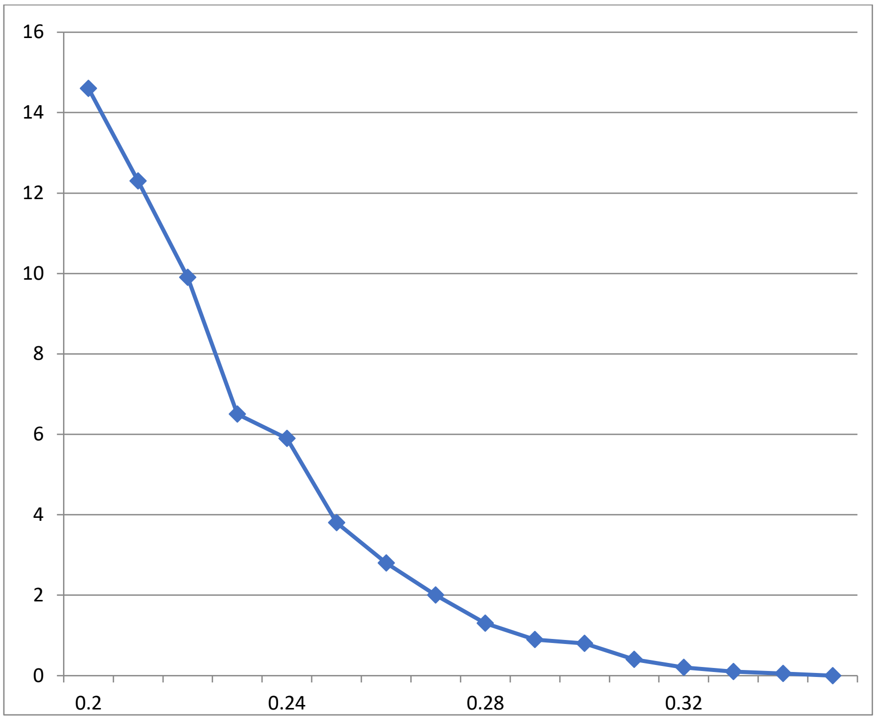

Fig. 9. Non-conformity rate (NCR) as a function of parallelism tolerance (t_0)

4. CONCLUSIONS

This paper presented a computational framework for modeling geometric deviations on planar surfaces manufactured using the Fused Deposition Modeling (FDM) process. The proposed approach is based on the discretization of a nominal planar surface and the superposition of three deviation modes representative of FDM process characteristics: a global surface orientation mode, a waviness mode associated with the material deposition process, and a random deviation.

The methodology was illustrated through a numerical case study involving a prismatic part with a functional planar surface. The resulting skin model surface was used to evaluate parallelism tolerance compliance by means of an extensive Monte Carlo simulation, allowing a quantitative analysis of the relationship between geometric deviations, tolerance limits, and the resulting non-conformity rate.

The manufacturing of test part on the FDM machine available in the laboratory, whose build volume is representative of desktop grade additive manufacturing systems commonly employed for research and prototyping purposes. The use of a relatively small planar surface makes it possible to isolate the dominant process induced deviations, such as surface orientation and waviness.

Although the present study focused on a simplified planar configuration and a controlled experimental context, the proposed modeling framework is generic and can be extended to larger surfaces, different surface orientations, and more complex toolpath strategies. Future work will address these extensions in order to further enhance the industrial relevance of the proposed approach.

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