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ORIGINAL CONTRIBUTION

Geometry Assurance Analysis Considering Riveting Distortion Effects Within The Aeronautical Domain

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Abstract— **Geometrical variations are intrinsic to all industrial manufacturing and assembly processes. Within the aeronautical domain, where there are many structural components on its products and small geometrical distortions have a great impact on the aircraft performance, the use of tools to estimate surface deviation plays a key role in defining well succeed manufacturing and assembly systems. Well-known methods to compute geometrical deviations nowadays consider statistical manufacturing process deviations and, in some cases, the flexibility of the assembly to estimate the final product surface distortion. The work presented herein describes a method that matches the deviations caused by the manufacturing process with deviations caused by the riveting process that is widely used in the aeronautical industry. The designed method was tested in an aeronautical commonly joint and showed that the riveting process plays an important role in amplifying surface errors. The finding underlines the importance of considering the riveting process effects on analyzing the geometrical variations for aeronautical product surfaces.**

Index Terms— **Geometry Assurance, Manufacturing Process Simulation, Aeronautical Manufacturing, Geometrical Distortion Prediction**

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I. INTRODUCTION

Geometry assurance is often referred to as the work aiming to reduce the geometrical variation and its effects on the final product function [1]. This knowledge area is particularly important in the aeronautical industry once the flight performance of the manufactured aircraft is directly linked with the geometrical quality of the assembled product. The high number of parts and the low values for position requirements in the aeronautical industry make the design and assembly process challenging.

To contextualize the challenge, Table I presents typical characteristics of the automotive (one of the most developed transport industries) and aeronautical industries in terms of dimensional requirements.

TABLE I
AUTOMOTIVE AND AERONAUTICAL INDUSTRIES DIMENSIONAL REQUIREMENTS [2]

	Automotive Industry	Aeronautical Industry
Typical position requirement	+/- 1.2 [mm]	+/- 0.1 [mm]
Product average lifespan	10 years	40 years
Average year production	100000 units	600 units

The final product variation is mainly a result of variation in the assembly process and part variation stemming from previous manufacturing and handling processes. Thus, from the geometrical assurance point of view, a successfully designed product can have a low sensibility to the parts variation. A product with great sensibility to parts variation can result in expensive and time-consuming trimming activities to fulfill assembly, functional, and esthetical requirements.

A product's key characteristic that uses a robust design concept is the insensitivity to part variation [3, 4]. The main concept of robust design and quality improvement was introduced by Taguchi [5], who divided the factors affecting a design concept into control factors and noise factors. Thus, the transfer function relating the control factor (inputs) to outputs determines whether variation can be amplified (sensitive concept) or suppressed (robust design concept), Fig. 1.

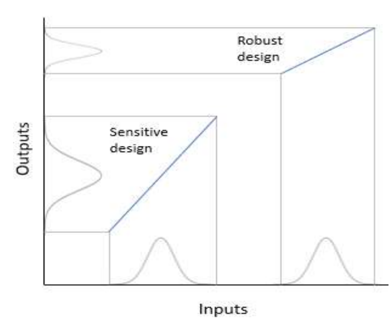

Fig. 1. Sensitive and Robust Design Concepts [3]

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Motivated by the challenge of developing a product design strategy that can provide geometrical robustness for the final product, this work presents an approach that considers for the final product distortion, accounting not only the manufacturing process variation but also the deviation caused by the assembly process which in the case of the aeronautical industry is mainly characterized by the riveting process.

Thus, a Monte Carlo approach is used to estimate the statistical geometrical distortion of a typical aeronautical assembly, and then riveting process distortion effects are implemented in the statistical results.

A. Assembly Variation Simulation

Manufacturing processes are affected by variation. Therefore, no final product looks the same from time to time, and in some cases, functional or esthetical requirements are not fulfilled. Completely avoiding variation is difficult, if even possible, and extremely expensive. Even though modern manufacturing processes achieve steadily increasing accuracy, it is widely acknowledged that geometrical deviations can be observed on every physical artifact [6]. But there are methods and tools to reduce the amount of variation and the effect of the variation [7]. Thus, there is a strong need for companies to manage these geometrical deviations throughout the whole product life-cycle [3]. Thus, geometry assurance activities can be found in all the different phases of the product realization loop, Fig. 2.

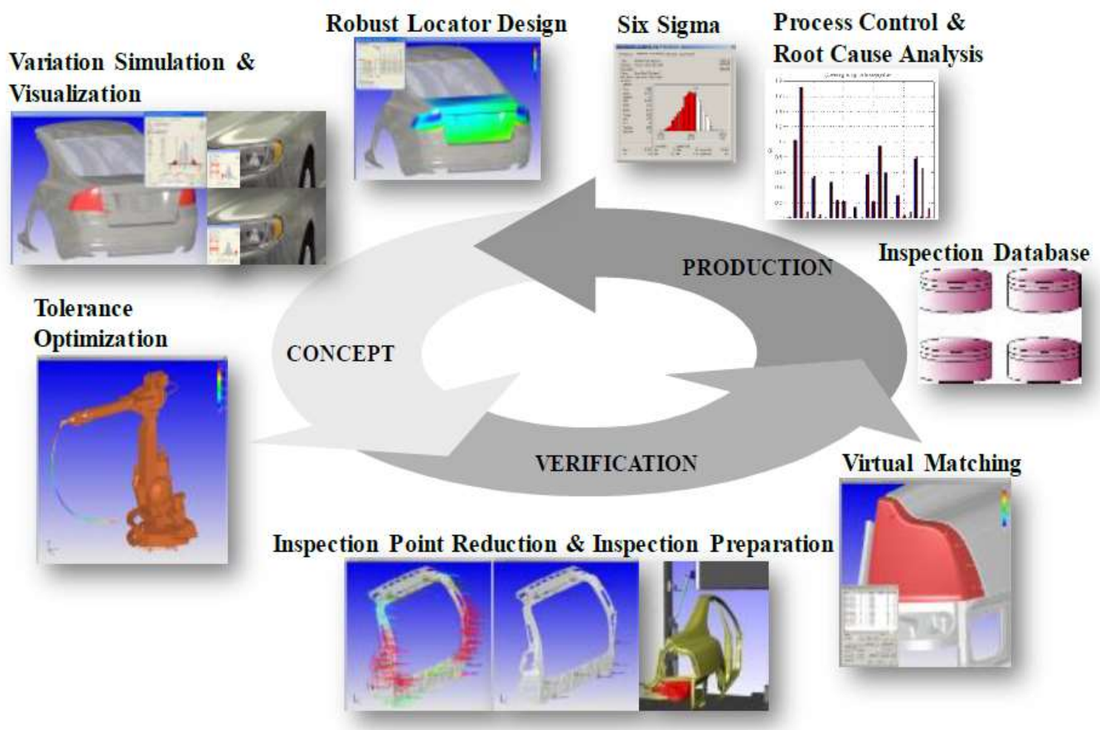

Fig. 2. Geometry assurance activities [3]

Intending to predict the geometrical outcome of an assembled product or sub-assembly as early as possible during the product development emerges the idea of establishing an approach that allows the geometrical variation simulation. Therefore, quantifying the magnitude of the variation of the nominal values is an important key characteristic. The inputs to a variation simulation consist of digital models of the parts to be assembled, and their tolerances (information about what variation can be expected for an individual part) are necessary. If any other factors influence the result, those should also be included [7].

Defining a good accuracy variation simulation procedure can allow the replacement of some tests on physical prototypes, shortening the lead times and reducing the risk of misjudgments.

For variation simulation, there are two main approaches to statistical tolerance analysis: Monte Carlo (MC) simulation-based approach, a deterministic method that is often based on Taylor's series expansion [8] and [3], and the MC simulation-based using Direct Monte Carlo (DMC) simulation by linearization. For a DMC-based variation simulation, distributions for all input parameters are defined. In each DMC iteration, values of the input parameters are randomly sampled from the defined distributions. The main idea of MC is to find a linear relationship between part and assembly deviations [3]

Different approaches for variation simulation are presented in the literature. Variation simulation considering non-rigid parts and assemblies is described in [7] and [1]. Jareteg et al. [9] show variation simulation for composites, and stress-based geometrical induced variation simulation in composites is treated [10].

In this work, the geometrical variation of the studied assembly is performed using Direct Monte Carlo approach.

B. Distortion Caused by the Riveting Process

Joint parts through the riveting process is the main manufacturing approach used to assemble aeronautical parts. This process is commonly used mostly for its reliability and robustness once this kind of joint approach is good for the joint's fatigue life.

Historically aeronautical manufacturers spend a great amount of time and money with rework on skins and segments through the assembly process once it is hard to preview the effect of induced deformation caused by the riveting process [11].

The riveting process induces deformation in the system due to the interaction of the rivet plastic deformation with the structural parts that are being joined. Thus, the rivet expansion on the hole yields deformation. In this sense, the problem emerges from the cumulative effect of each rivet expansion that can cause significant geometrical changes in structural segments [12].

Mu et al. [13] show Equation 1 to calculate the diametral expansion (Δ) of the sheet holes during the confirmation process of a slug rivet, presented in Fig. 3.

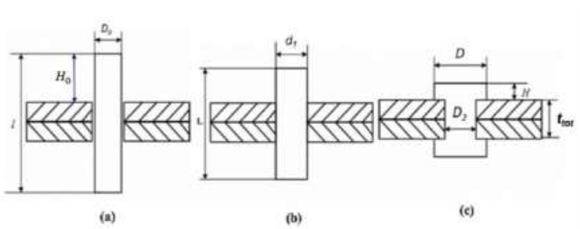

Fig. 3. Algebraic formulation variables [13]

$$\Delta = \left\{ \left[\frac{D_0^2 l}{d_1^2 t_{tot}} - \frac{8HF_{sq}}{K\pi t_{tot} d_1^2} \left[\ln\left(\frac{2HD_0^2}{D_0^2 l - d_1^2 t_{tot}} \right) \right]^{-n} \right]^{1/2} - 1 \right\} \tag{1}$$

Figueira [12] presents a work that brings an analytical approach to calculating the expansion of the riveting line from each diametral expansion. The analysis starts from the expression of squeezing force that came from Equation 2 and Equation 3 where K_r is the rivet material strength coefficient, n_r is the rivet strain hardening exponent, D_0 is the rivet driven-head initial diameter, and D is the rivet driven-head final diameter.

$$F_{sq} = \frac{\pi}{4} D^2 K_r \left\{ \ln\left(D/D_0\right) \right\}^{n_r} \tag{2}$$

In addition, it is deduced from the volume conservation equation for the rivet that the final rivet diameter inside the hole can be analytically calculated by:

$$D_0^2 H_0 = D_1^2 L_1 = D_2^2 t_{tot} + D^2 H \tag{3}$$

And finally:

$$D_2 = \sqrt{\frac{D_0^2 H_0 - D^2 H}{t_{tot}}} \tag{4}$$

Equation 4 is particularly important once it makes it possible to calculate the final diameter of the rivet inside the hole after the riveting process from rivet driven-head geometries and packaged thickness.

Thus, the constructive equations are presented to find the final hole diameter (D_2) after the riveting process from the rivet material proprieties (K_r, n_r), sheet material proprieties (K, n), and the final diameter of the rivet driven-head (D):

$$\left(2\ln\left(D/D_0\right)\right)^{n_r} - \left(2\ln\left({}^{D}/D_0\right)\right)^{n_r} = \frac{K}{\sqrt{3}K_r}\left(\frac{2}{\sqrt{3}}\ln\left({}^{D_2}/D_1\right)\right)^n \tag{5}$$

Therefore, Equation 6 presents the riveting radial stress in the hole edge:

$$\sigma_{rr} = \frac{K}{\sqrt{3}}\left(\frac{2}{\sqrt{3}}\ln\left(D_2/D_1\right)\right)^n \tag{6}$$

II. MATERIALS AND METHODS

The proposed method presented herein is elaborated and developed following four main steps, Fig. 4:

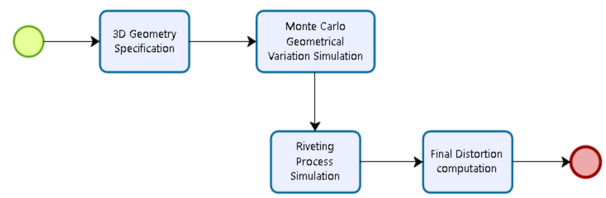

Fig. 4. Bricks Production and Environmental Pollution Waste

A. 3D Geometry Specification

At this phase, a virtual specimen is presented, considering the geometrical characteristics of a typical aircraft wing structure.

Therefore, the designed geometrical specimen should be representative enough of the aerostructures assembled on the shop floor of the aeronautical manufacturers' companies. Thus, taking as reference typical structures used on wing assembly, Fig. 5, the study geometry is proposed without the hyper-supportive structures, Fig. 6.

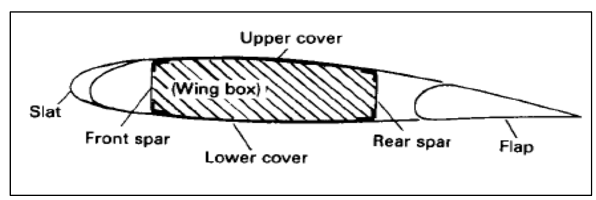

Fig. 5. Typical wing structures [14]

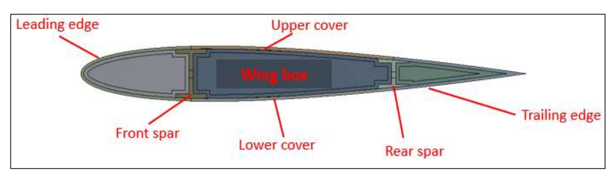

Fig. 6. 3D Geometry model structures

B. Monte Carlo Geometrical Variation Simulation

Considering the typical deviation of the aeronautical structural parts manufacturing process, a Direct Monte Carlo (DMC) assembly simulation is performed for 1000 units.

Thus, the analysis is conducted considering the interaction of the upper cover and the wing box on eight selected points: the skin corners (P1, P3, P5, and P7) and the central point of each riveting line (P2, P4, P6, and P8), Fig. 7.

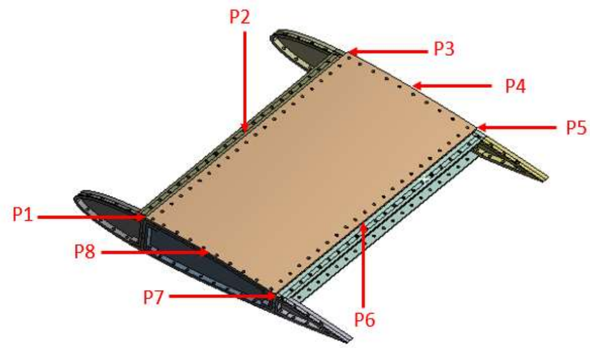

Fig. 7. Dimensional analysis points

C. Riveting Process Simulation

The stress on the hole edged after the riveting process is calculated from the presented analytical model. The found value is used to feed the numerical simulation, and the deformation caused by the riveting process is obtained, Fig. 8 and Fig. 9.

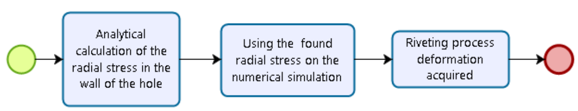

Fig. 8. Riveting Process Simulation Steps

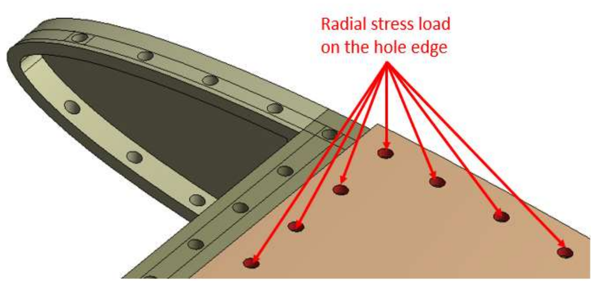

Fig. 9. Calculated Radial Stress Implemented on the Numerical Simulation

D. Final Distortion Computation

The distortion distribution curves obtained by the Direct Monte Carlo simulation are corrected with the results obtained on the riveting process simulation step by adding the numerically calculated distortion to the distribution curves means, Fig. 10.

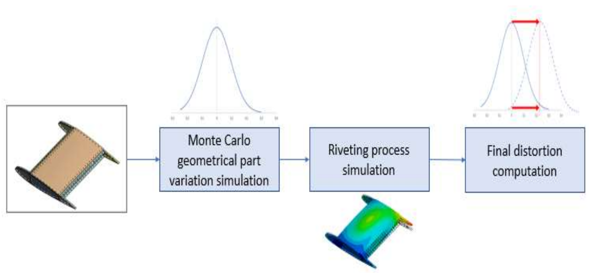

Fig. 10. Final Distortion Computation

III. RESULTS

TABLE II
NORMAL CURVE DISTRIBUTION PARAMETERS RESULT FOR THE MONTE CARLO SIMULATION

Point	Mean	Standard Deviation
P1	0,001	0,1628
P2	0,013	0,1649
P3	-0,004	0,1681
P4	0,004	0,1653
P5	-0,005	0,1674
P6	0,003	0,1539
P7	0,004	0,1694
P8	0,007	0,1638

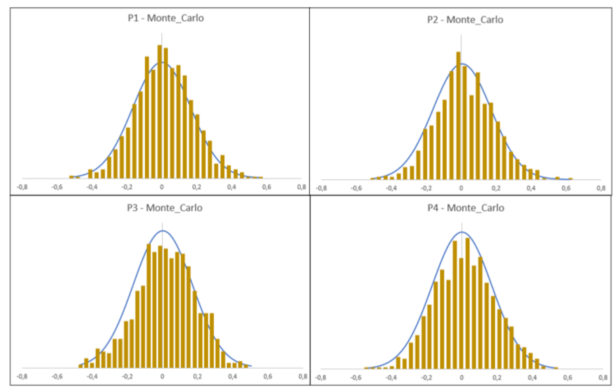

Fig. 11. P1 to P4 Monte Carlo Simulation Results

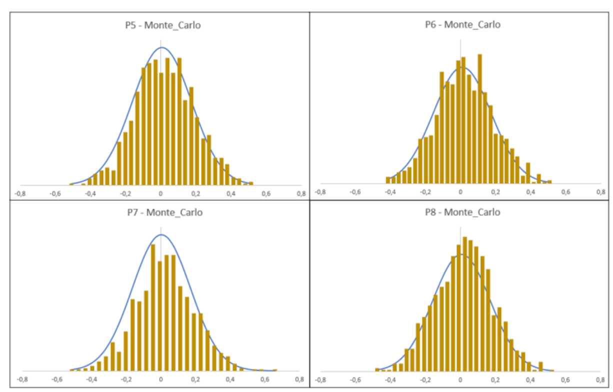

Fig. 12. P5 To P6 Monte Carlo Simulation Results

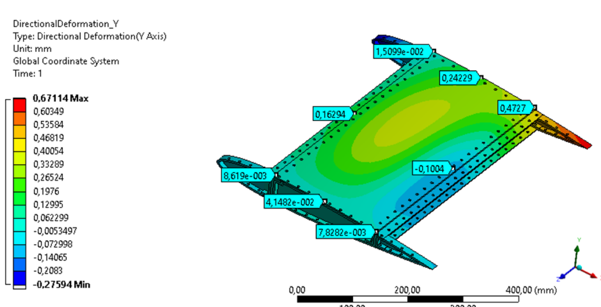

Fig. 13. P1 to P8 Riveting Induced Deformation Results

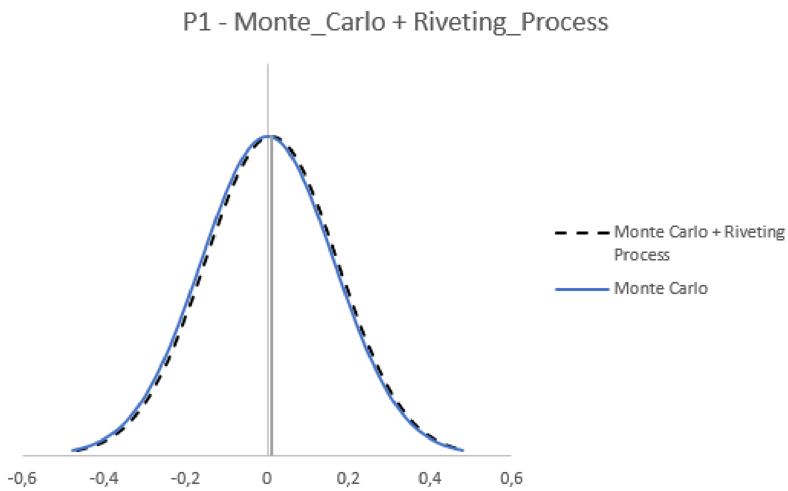

Fig. 14. P1 Final Deformation Results

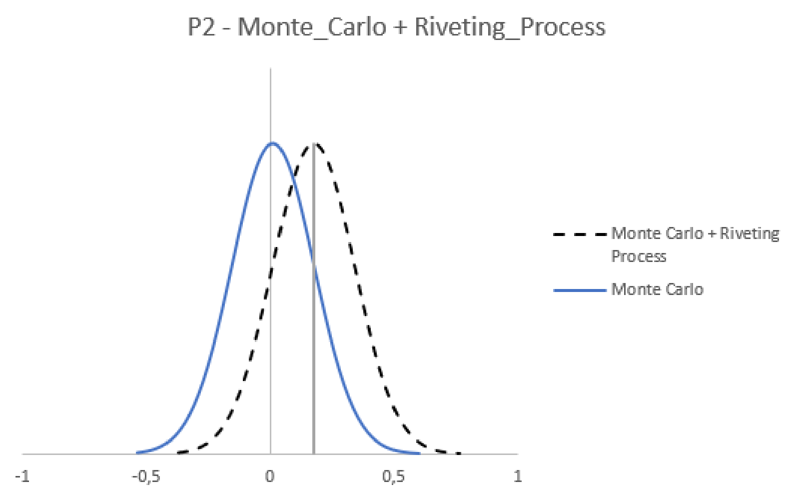

Fig. 15. P2 Final Deformation Results

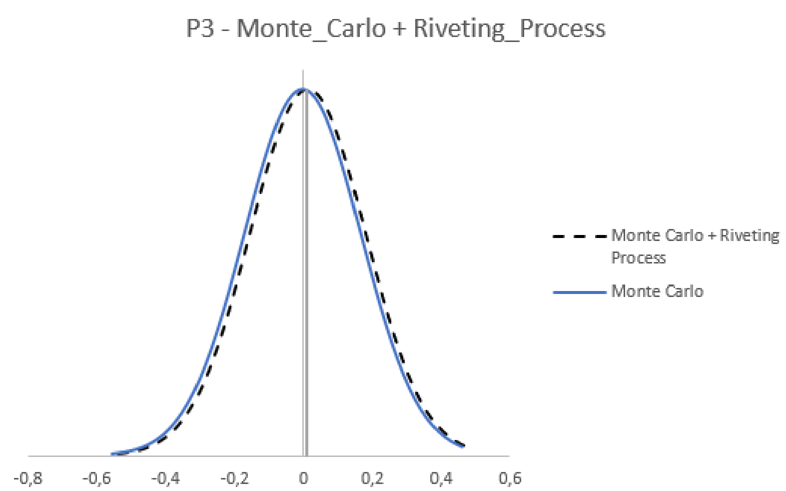

Fig. 16. P3 Final Deformation Results

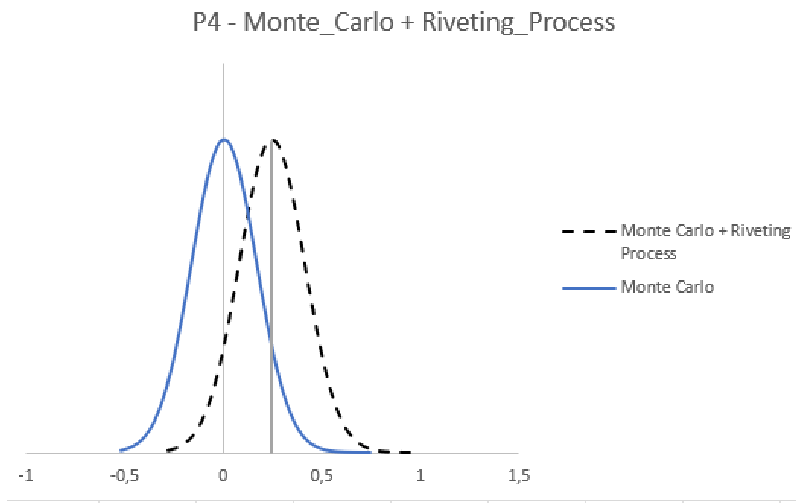

Fig. 17. P4 Final Deformation Results

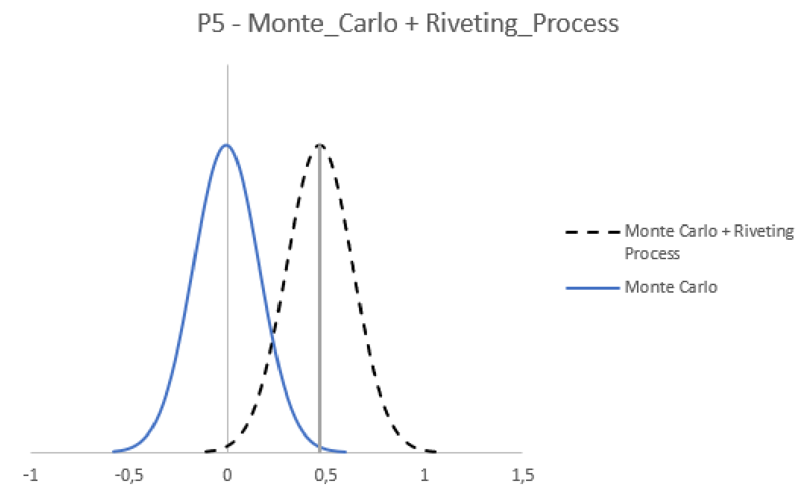

Fig. 18. P5 Final Deformation Results

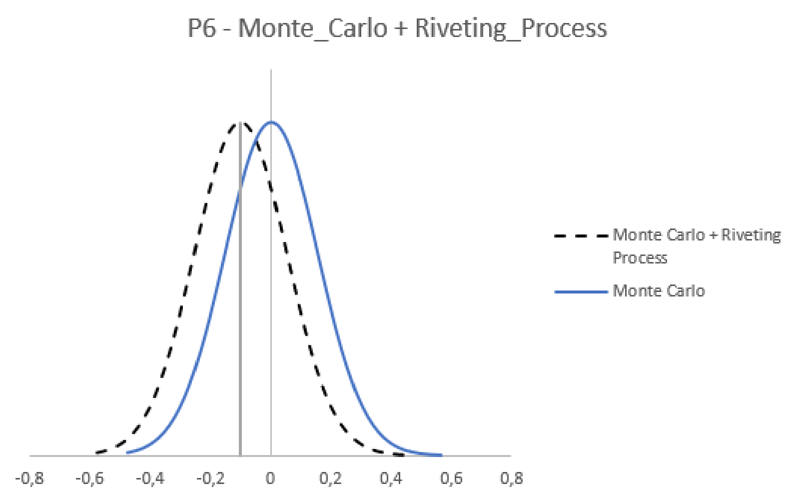

Fig. 19. P6 Final Deformation Results

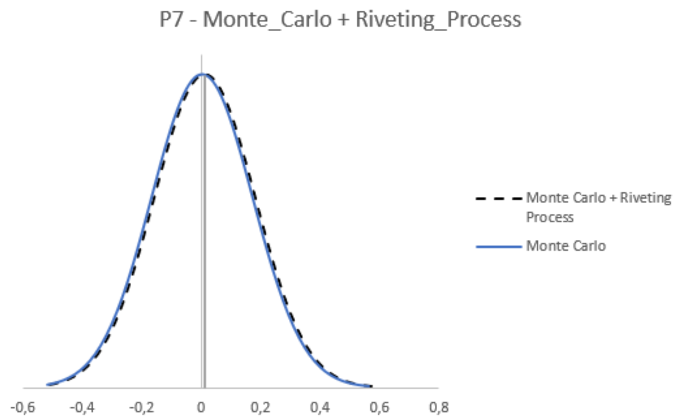

Fig. 20. P7 Final Deformation Results

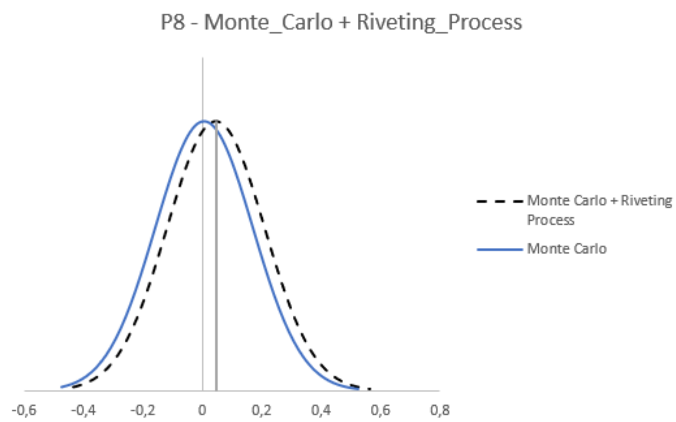

Fig. 21. P8 Final Deformation Results

TABLE III
NORMAL CURVE DISTRIBUTION PARAMETERS RESULT FOR FINAL DEFORMATION

Point	Mean Before Riveting Process [mm]	Mean After Riveting Process[mm]]	Standard Deviation
P1	0,001	0,010	0,1628
P2	0,013	0,1756	0,1649
P3	-0,004	0,0113	0,1681
P4	0,004	0,2458	0,1653
P5	-0,005	0,4679	0,1674
P6	0,003	-0,0997	0,1539
P7	0,004	0,0115	0,1694
P8	0,007	0,0467	0,1638

IV. DISCUSSION

Table II shows the mean value and the standard deviation for the assembly of the skin and the wing box. Typically, the manufacturing processes machining those parts are calibrated to have a mean value of 0 [mm] of distortion, which is corroborated by the results presented in the second column of the table.

The third column of Table II reveals the standard deviation of the assembly on the eight analyzed points. The magnitudes of the presented deviations are close for all the eight analyzed points. This behavior is expected once all the eight analyzed points are subjected to the same mechanical interface and manufacturing process. Fig. 11 and 12 depict the Monte Carlo simulation re-presenting the Table II results graphically.

Fig. 13 shows the deformation caused by the riveting process estimated using Equation 6 to calculate the radial stress and apply these values to the hole edges in the numerical simulation.

The region of the points P1, P7, and P8 presented a low magnitude of deformation, which is expected for the wing root region given its greater rigidity. However, analyzing the behavior of the points P2, P3, P4, P5, and P6, a deformation magnitude of tenths of millimeters is observed.

In the aeronautical industry, Monte Carlo simulation is commonly used to estimate the range distortion expected for an assembly. Nevertheless, those simulations of the distortion caused by the riveting process are rarely considered.

The presented results showed that the magnitude of the distortion caused by the riveting process could be greater than the ones caused by the manufacturing process variability.

Fig. 14 to Fig. 21 presented the distortion curve translation caused by the addition of the magnitude of the simulated deviation caused by the riveting process and added to the mean of the distortion curve.

In an industry with tenths of millimeters as typical surface tolerance, a product out of the specifications may imply non-delivery of estimated project requirements affecting product functionality.

Thus, the riveting process distortion simulation can avoid significant rework on the shop floor of the factory and reduce assembly costs once nonconformities can be better predicted before the assembly process starts.

Finally, Table III summarizes the results of the combinate strategy of Monte Carlo and riveting process simulation, highlighting the differences in the means of the resultant distributions.

V. CONCLUSION

This work aimed to use a simulation approach to estimate the absolute surface deviation of an aeronautical product considering the distortion caused by the variation of the manufacturing process and the distortion caused by the riveting process. Based on the obtained results, the following can be stated:

1. For some points of the assembly (points P2, P4, and P5), the riveting process can contribute to bigger mean distortions magnitudes than the ones caused by the assembly process;

2. For other points (points P1, P3, P6, P7, and P8), the riveting process can be responsible for increasing the number of assemblies on the tail of the distribution curve with non-conformances.

To continue the presented work, the following is suggested:

1. Implementation of non-rigid characteristics to the parts of the simulation. This can improve the accuracy of the distortion estimation;

2. Consideration of temperature distortion effects. For big structures such as wings and fuselages, the differences in temperature in several regions of the structure can induce significant surface deformation;

3. Determination of the gravity deformation effects. The gravity can accommodate the structure so that the geometrical distortion can be increased.

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