Title:
Circularity Compensation by CAD Modeling in Rapid Prototyping of Cylindrical Parts

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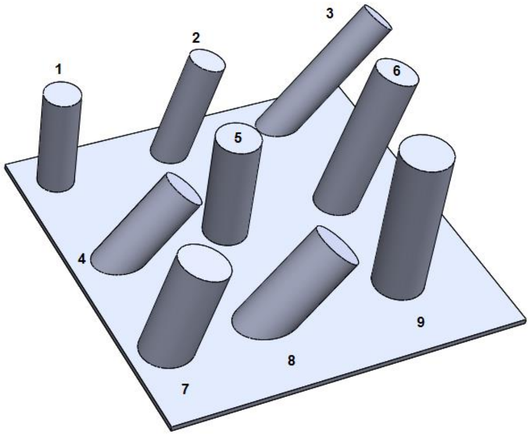
Introduction:
This work presents an approach to error compensation in rapid prototyping of parts having circular geometries. The proposal follows the literature research line dedicated to verify the quality of produced parts in additive manufacturing process. In this respect, some authors proposed regular geometry artefacts to evaluate the quality of parts produced by additive manufacturing. Moylan et al. [5] reviewed the tests parts used in additive manufacturing and proposed a new part with features observed in the previous ones. This new part is known as NIST test part [2]. Yang and Anam based their studies on dimensioning and tolerancing methods and proposed a redesigned the NIST test part [7]. Islam and Sacks observed that designed flat surfaces presented a flatness error associated to z direction (height) of the 3D printer that after error correction was reduced to 25.52 % in average [3]. Martorelli et al. [3] investigated geometric errors of flatness, circularity and cylindricity in manufactured models. Medhi-Souzani et al. [4] investigated the use of artefacts with freeform surfaces to evaluate the performance of manufacturing freeform surface parts. A recent review on artefacts to verify performance was presented by Rebaioli and Fassi [6].

The experimental work was carried out by manufacturing a standard part having cylinders, designed in Catia software and manufactured by rapid prototyping. The first part was designed having as variables the diameter, the height and the inclination angle, settled at three levels each. Manufacturing took place starting from CAD model in a STL file and using polymer ABS. This part was measured using a Caliper to determine the errors in diameter, height and angle, and a Coordinate Measuring Machine (CMM) to determine the circularity deviations. A revised CAD model was designed with corrections in circularity and a new part was manufactured and measured. A second part was produced as a verification part extending for other diameters. It was designed having circular steps with diameters ranging from 10 to 90 mm. Circularity was measured with a CMM and error compensation was introduced in the redesigned part.

Experimental:

Two test parts were designed in Catia software to evaluate a 3D printer. The part 1 has cylinders fixed to a squared basis and some geometry variables were changed. The diameter, the height and the angle of inclination in respect to the basis were changed in three levels each, resulting to nine cylinders distributed according to a Latin Squares design of experiment (DOE) over the basis. The Analysis of Variance (ANOVA) was additionally applied to verify the influence of these variables in diameter and height results [1]. Circularity was determined by measuring the radius deviations in respect to least squares circle diameter calculated. Figure 1 presents the designed part and the designed variables in its levels.



Cylinder	Angle (°)	Diameter (mm)	Height (mm)
1	90	10	30.000
2	75	10	32.371
3	50	10	45.013
4	50	12	30.000
5	90	12	32.371
6	75	12	45.013
7	75	14	30.000
8	50	14	32.371
9	90	14	45.013

Fig. 1: CAD model of part number 1, with cylinder data. DOE array in Latin Square, with control variables at respective levels.

A Computer-Aided Design (CAD) model was built in Catia software using the tools available to fit regular geometries. After concluded, a mesh with 31668 triangles was fitted and the model was saved in STL file before sending to the 3D printer.

A low-cost 3D printer manufactured by Leapfrog, model Creatr, was used to produce the parts. This machine has an accuracy of 0.05 mm in x,y and z axis, according to the manufacturer. The deposition path followed the x direction with the speed set at 60 mm/s. The parts were produced in ABS (Acrylonytrile-Butadiene-Stirene) polymer.

The measurements were performed by using a Caliper and a Coordinate Measuring Machine (CMM). The Caliper used was made by Starrett, digital model, having a resolution of 0.01 mm. The circularity deviations were determined with a Mitutoyo Cantilever manual CMM, with a resolution of 0.001 mm each axis and with a standard measurement uncertainty of 0.003 mm in work volume.

After measurement of the first part, the errors in diameter, height and circularity were compensated by changing these parameters in a new CAD model. This new CAD mode, having the same configuration showed in Figure 1, was produced and measured to compare with first one.

A third part was designed and manufactured with different diameters, as showed in Figure 2. The diameters were changed from 10 to 90 mm. The same conditions of material, printer, speed, etc, were adopted in this new processing. The part was measured to determine the errors in diameter and circularity and the errors found were corrected in the design of a new part. The corrected part was produced and measured to evaluate the efficiency of this proposal.

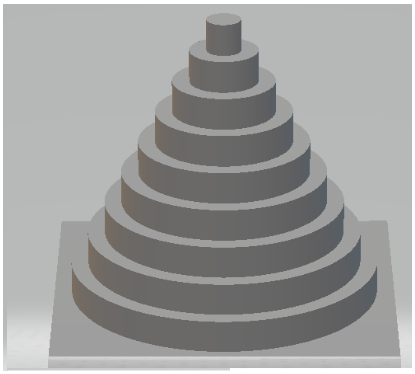


Fig. 2: CAD model of part number 2, with circular steps, ranging from 10 to 90 mm in diameter.

Results:

The investigation on error compensation began with the design and fabrication of the Part 1. The produced part was measured and its circularity characteristics was measured and represented in polar graphs. It was observed a circularity deviation with similar aspect for almost all cylinders, having approximately 0.2 mm more than the diameter in x-axis and zero deviation in y-axis, as showed in Figure 3 (previous). These errors were compensated through a new redesigned CAD model, followed by manufacturing again this part 1. The residual circularity was determined and it is presented in the same Figure (error corrected). Compensation proved successful to reduce the circularity to levels above the prototyping machine resolution.

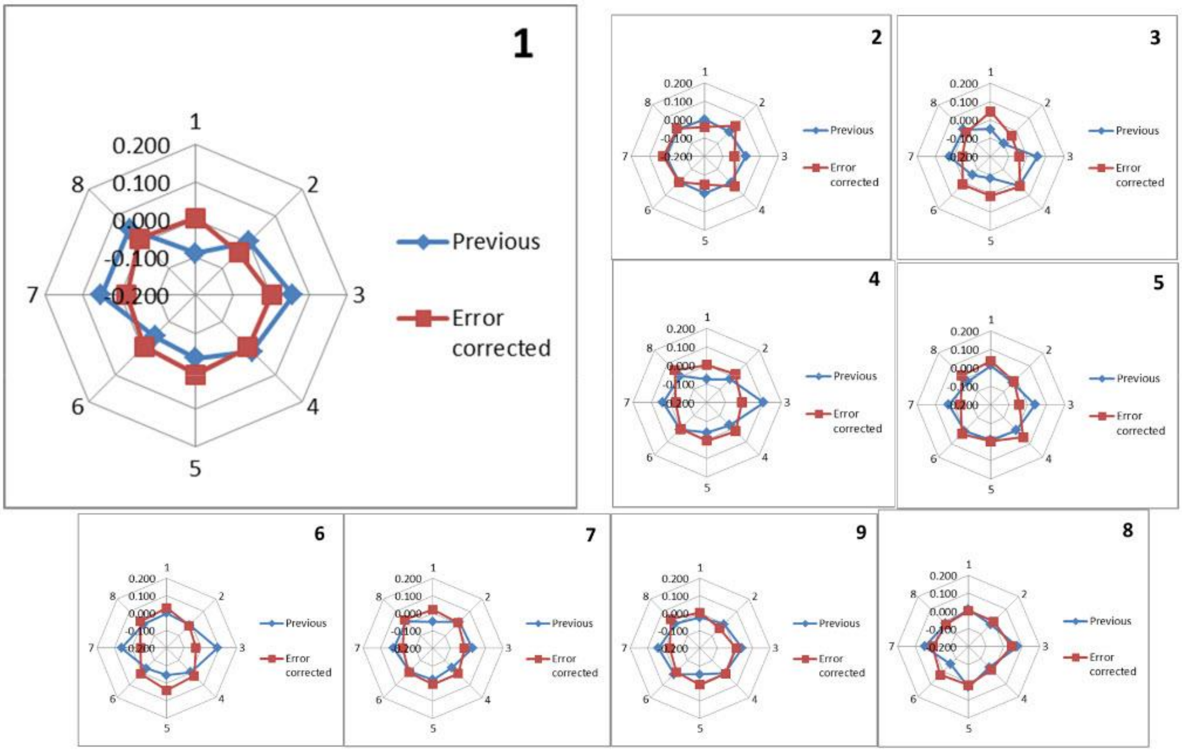


Fig. 3: Circularity errors in cylinders after 1st processing (previous) compared with 2nd processing (error corrected). Part number 1.

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The same study was carried out with the second part (part 2) having circular stairs. A first CAD model was designed and produced. The mean errors in diameter and circularity, that was nearly 0.2 mm in x-axis direction, were determined and compensated in a new redesigned CAD model. The part was produced and the residual circularity was determined. Figure 4 shows the circularity errors for the studied diameters, with previous and error corrected values. It was observed a reduction in circularity that was achieved by compensation with a constant circularity characteristic.

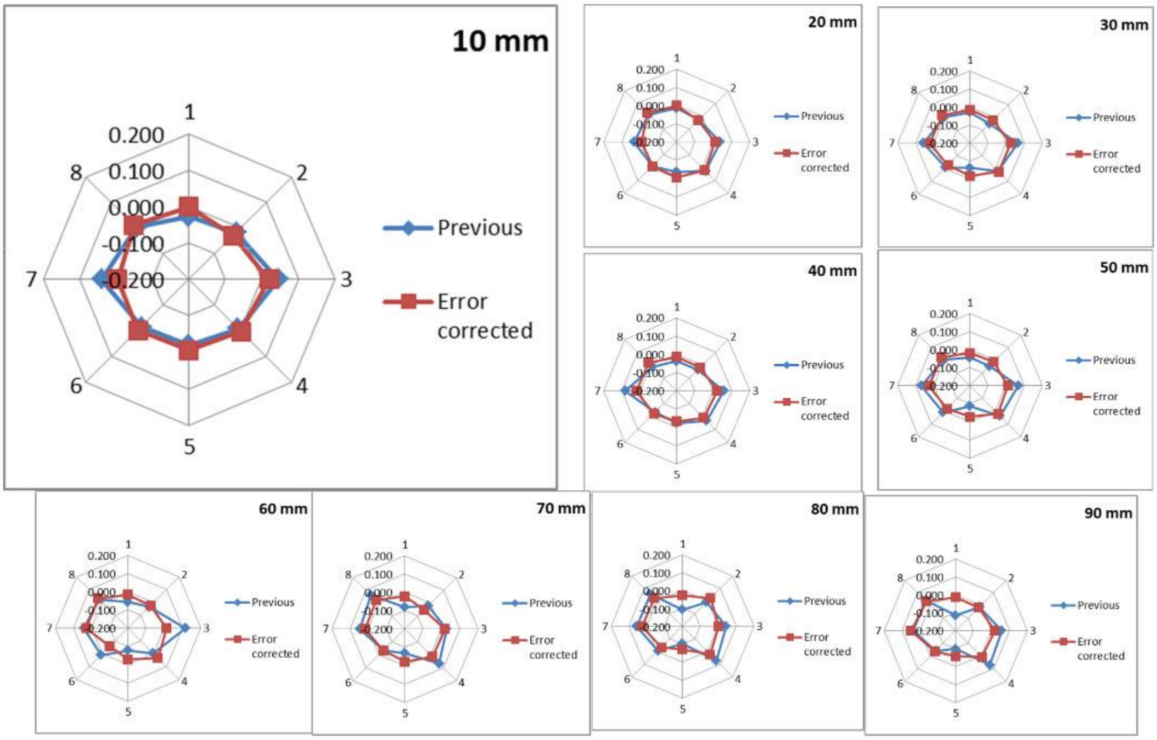

Fig. 4: Circularity errors for part with circular steps, for diameters ranging from 10 to 90 mm, manufactured after systematic and circularity errors compensation (4th processing). Part number 2.

Additionally, the Analysis of Variance (ANOVA) showed that, for the range of values of the studied parameters, there were no variable that promoted significant changes in mean error in diameter and height, despite of circularity produced a regular characteristic. Table 1 presents the ANOVA results.

FV	SQ	GL	QM	Fc	p
Diameter	6.66667E-05	2	3.33E-05	0.08	0.92
Height	0.000866667	2	0.000433	1.08	0.48
Angle	0.003466667	2	0.001733	4.33	0.19
Residual	0.0008	2	0.0004		
Total	0.00520	8			

Tab. 1: ANOVA results of mean variation in diameter.

Conclusions:
The proposed approach contributed to improve the quality of simple parts having regular geometries at reduced cost and using a simple method. The error correction for circularity, applied over the CAD model, proved successful in conical parts of dimensions until 90 mm in diameter. For small diameters and heights, the variables investigated do not influenced the mean errors, as presented by ANOVA results, but improve in precision was accomplished by analyzing the geometry.

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