# STUDY OF CAD/CAM PROCESSING OF FREEFORM SURFACES

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***Abstract.*** *This work presents a study of Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) processing of freeform surfaces. The steps involved in measurement, CAD model reconstruction and CAM manufacturing were addressed and the deviations between points of part surface and fitted CAD model were determined and considered as evaluation parameters. A small freeform runner with dimensions 300 mm long and 4 mm large was measured using an Articulated Arm Coordinate Measuring Machine (AACMM) with a rigid probe and needle stylus. A grid of points was superimposed over the surfaces and the points were determined following transversal paths. The data points were exported and the CAD model was built using Rhinoceros software. Based on this model, SURFCAM software was used to generate the tool path that was implemented in a numerically controlled three axis milling machine Feeler Fv-1000 with Mitsubishi M6 command. The part was milled in RenShape 5179 epoxy-based composite and measured using the AACMM. The deviations between measured runner and CAD model (1) and between CAD model and CAM manufactured runner (2) were determined and the results showed small values with a maximum of 0.5 mm. There were some differences in mean and standard deviation in cases (1) and (2), as the mean was 0.076 mm (1) and 0.132 mm (2) and the standard deviation was 0.086 mm (1) and 0.090 mm(2). The most pronounced deviations in CAD/CAM processing were associated to the CAM manufacturing process as the mean variation in edge deviation was greater than the mean in CAD model. This result was associated to the constructive characteristics and geometric errors of milling machine used.*

***Keywords****: CAD/CAM, freeform surfaces, reverse engineering*

## 1. INTRODUCTION

Reverse engineering is a process that intends to generate a copy of a physical prototype at industrial level. This process involves the prototype measurement and the construction of a Computer-Aided Design (CAD) model, followed by the manufacturing of the part using Computer-Aided Manufacturing (CAM) process through rapid prototyping or automatic milling machines. This process is also applied in industry to design new parts, to reproduce an existing product, to recover damaged or defective parts and to design molds (Bagci, 2009).

The CAD/CAM technology may be considered as the core of the reverse engineering process. This technology involves the use of contact or contactless measurement instruments to carry out measurements, dedicated software to perform the construction of CAD model and to generate the CAM processing programs and automatic machine tools to manufacture the parts.

The first step in CAD/CAM processing is the part measurement. The suitable measuring system is selected according to the degree of precision demanded by the part tolerances. The most commonly used instruments are Coordinate Measuring Machines (CMMs) with contact or non-contact probes to capture points on the surfaces, but other optical devices like laser scanner are growing in application. The second step is transferring the measurement data to CAD software in order to develop a virtual part model, the so-called CAD model. At this point, the data points are adjusted to create the surfaces that match the prototype. The third step is the part production that is accomplished through the CAM processing. Automatic machines with Computer Numeric Control (CNC) are used to perform this task, sometimes directly producing the part otherwise manufacturing the molds that will be used in a further processing step.

There are many products manufactured by CAD/CAM processing that uses regular geometry like planes, cylinders and circles, as machine parts and mechanical components. Therefore, the design requirements are demanding the specification of surfaces having freeform geometry. Berg (2002) detached that regular-shaped parts were quite studied in the past and freeform features are growing in application and demanding more research efforts. For instance, in automotive industry, designers may employ freeform surfaces to establish geometry according to the needs of aerodynamics. The same applies in aerospace and ship building industries where there is a need of curvatures that addresses questions like aerodynamics. Other applications may be found in optics, energy and medicine fields (Savio *et al.*, 2007).

Savio *et al.* (2007) presented an overview of the recent trends in measurement of freeform surfaces. The authors categorized these efforts in two general approaches, direct and indirect comparison. Direct comparison involves verification of the surface in respect to a master template that may be carried out with a measuring microscope, but its limitations are related to accuracy, speed and request of dedicated equipment. Indirect comparison involves verification of the surface in respect to a computerized model of the part as the CAD model and the measuring system may be selected among several different options.

Verification methods using indirect comparison may be classified in categories and are summarized as: *i)* systems for large scale metrology as laser tracking interferometry, photogrammetry and laser radar, used to inspect large parts; *ii)* coordinate measuring machines, using contact or non-contact probes, commonly used when accuracy and flexibility are demanded; *iii)* stand still optical systems as photogrammetry and interferometric techniques, applied to inspect by optical triangulation, as in fringe projection and fringe reflection, used to inspect high precision optical parts; *iv)* interferometric techniques as computer generated holograms (CGH), sub-aperture interferometry and curvature sensors, for fast measurement with sub-nanometer resolution; *v)* profilometry using an stylus drawn over the surface, having nanometric resolution; *vi)* systems for micro/nano scale metrology, as miniaturized probing systems, scanning force microscopy and atomic force microscope; *vii)* others like X-ray tomography and ultrasonic sensors (Savio *et al.*, 2007). Some of these techniques were investigated and compared by Barbero and Ureta (2011) in respect to the accuracy during digitization of surfaces.

The inspection of a freeform surface is based on a group of points distributed over the surface. Some variables that influence the accuracy are the sampling strategy, involving the number and location of the points over the surface, and the probe path planning. The points are acquired using a selected measuring system and these data are exported to a CAD software to build the computerized model (Savio *et al.*, 2007).

Freeform curves and surfaces are usually described by parametric representations as B-Splines and Non-Uniform Rational B-Splines (NURBS). These models have advantages over non-parametric ones as facilities in computational processing of data and graphics representations (Piegl and Tiller, 1997). The NURBS are considered the industrial standard for geometry representation in CAD applications as they may be used to represent freeform and regular surfaces, as cylinders, planes and spheres. There are some cases where fitting a CAD model involves the registration of a few different views of the object measured with particular setups and solutions in hardware or software are demanded. Filtering methods may be applied to separate form from other geometries and to eliminate outliers, such as linear, morphological, robust and segmentation filters. Alignment operations are demanded to acquire agreement between measurement and part coordinate systems, following a two-steps sequence involving coarse and fine alignment (Savio *et al.*, 2007).

Evaluation of measurement may be performed using 3D software colored maps to present the deviations from the nominal model. In addition, special parameters may be determined and curvature evaluation may be presented in graphics. Despite error sources in measurement are similar to regular geometries, there are some additional error sources that must be considered, as probe tip radius compensation, errors associated to optical system measurement as local curvatures and light scattering from surface, deformation effects and software errors originated from registration and filtering. Uncertainty must be addressed and some research guidelines are using calibrated parts, multiple measurement strategies and computational simulation (Savio *et al.*, 2007).

The equipments commonly used to produce parts with freeform surfaces are 3- and 5-axis CNC machine tools. The 5-axis CNC machines have three linear translation movements, such as 3-axis CNC machines, plus two rotation movements. A comparison of these machines was presented by literature showing that 5-axis can produce high precision freeform surfaces while 3-axis have better stiffness and lower cost (Lasemi *et al.*, 2010).

The CNC machining operation is usually carried out in steps and classified as rough, semi-finish, finish, clean-up and final polishing and treatment. Rough operation is used to remove most of the material in order to approximate the surface shape. Finishing operation improves the rough one in order to obtain the exact shape. Clean-up is applied to remove some remaining uncut material. These operations must be planed to avoid the presence of defects known as gouges, produced by the contact of the tool with the part. The gouges may be local, rear or global, depending on which section of the tool is causing this defect, and literature points out some techniques recommended to avoid gouging (Lasemi *et al.*, 2010).

The machining operation is programmed by indicating the cutter location points required to remove the material, considering the tool path planning, the tool orientation, the tool size and shape, the spindle speeds and the travelling velocity of the tool tip. The tool path planning is addressed by considering surface quality and time spent and aspects as path topology and path parameters must be defined. The tool orientation must vary smoothly in order to reduce time operation and avoid gouging. The tool geometry is selected according to the machining operation and the tool type and size parameters are defined to minimize tool changes and machining cost. These topics are under investigation by researchers (Lasemi *et al.*, 2010).

Applications of CAD/CAM techniques to manufacture parts with freeform surfaces were reported by literature. Witkowski *et al.* (2006) compared three commercial CAD/CAM systems used to manufacture titanium dental restorations. Williams *et al.* (2006) used CAD/CAM technology to manufacture denture framework using rapid prototyping process. Song *et al.* (2007) developed a CAD approach to design a dental prosthesis that was validated using CAM manufacturing. Rudolph *et al.* (2007) investigated dental freeform surface manufacturing and addressed the quality of digital data, the surface type and teeth shape over accuracy. Piratelli-Filho and Motta (2007) studied the performance of measurements taken with an Articulated Arm Coordinate Measuring Machine (AACMM) of a dental prosthesis CAD model reconstruction. Piratelli-Filho *et al.* (2009) developed a study on reverse engineering of turbine runners were CAD modeling was investigated with an AACMM. Aspects involved in measurement, CAD modeling and CAM manufacturing is also recent topics of research (Lasemi *et al.*, 2010; Barbero and Ureta, 2011).

This work presents a study of CAD/CAM processing of freeform surfaces. The steps involved in measurement, CAD model reconstruction and CAM manufacturing were addressed. The analysis of the process was conducted by plotting the deviations between surface part points and CAD model fitted and between CAM manufactured surface points and CAD model fitted.

## 2. CAD/CAM PROCESSING

A small freeform part was used to perform the experimental study. It was used a helicopter double runner propeller as prototype. The propeller was manufactured with polypropylene using injection molding process and each runner had dimensions 300 mm long and 4 mm large. Figure 1 shows this runner.

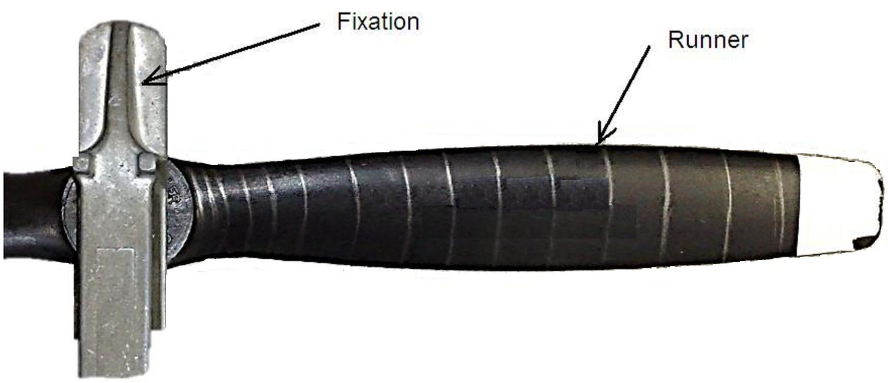


Figure 1. Runner used to carry out measurements.

The propeller was rigidly fixed at a cast iron base to perform the measurements. It was used an Articulated Arm Coordinate Measuring Machine (AACMM) manufactured by Romer, model Arm 100, with a spherical work volume of 2.5 m in diameter. The machine was calibrated and the performance was determined by the expanded measurement uncertainty (95%) of 0.06 mm in length and the probe repeatability uncertainty (95%) of 0.016 mm. A rigid probe with a needle stylus was used to capture the point coordinates on the surfaces. The software G-Pad was used to process information from AACMM data points.

As polymeric materials have low stiffness, especial attention was done in respect to the force applied by the probe over the measured surface to avoid elastic deformation and measurement errors. The measurement strategy was applied superimposing a grid of points over the surfaces and the points were determined following transversal paths. Fourteen transversal lines were traced on the surface, whose distance one to another was variable and depending on the curvature of the surface. Ten points were captured over each line in sequence using the AACMM. Additionally, points were determined in two lateral lines in longitudinal direction. Only one face of the runner was measured, together with the circle determining the propeller central cylinder. The groups of points obtained were saved and exported in IGS data format.

The data points were imported using Rhinoceros CAD software. The groups of points corresponding to measured paths on part surface were fitted to curves based on Non-Uniform Rational B-Splines (NURBS) models. These curves were then joined together in a freeform surface represented by NURBS model. The contour points in longitudinal direction were fitted to NURBS lines and the circle was used to fit the central cylinder of the propeller. The CAD model was exported in *parasolid* data format.

Some software commands used to fit the surfaces have to be identified. The lines of the grid (characterizing the measurement strategy) were measured twice and they were fitted to only one mean line using the command *Mean curve* of the Rhinoceros software. The fitted curves were smoothed by applying the command *Rebuild*, using the 10 points measured by defined line and a NURBS curve of 3$^{rd}$ degree was adjusted. The curves were converted into a surface by applying the command *Patch*. The cylinder of the propeller was created by selecting the measured circle and using the command *Extrude*. Finally, the cylinder and the runner surfaces were joined together by applying the *Blend surface* command.

The surface was manufactured in a numerically controlled three-axis CNC Machining Center, from Feeler model Fv-1000 with Mitsubishi M6 command. The machine has a work volume of 1000 x 500 x 505 mm defined by displacement in axis x, y and z, respectively, and parts having a maximum of 500 kg in weight may be placed over its 475 mm x 1150 mm table. The machine spindle speed may be adjusted between 50 and 8000 rpm and the feed rate may be adjusted at a maximum of 10000 mm/min. Processing stets may designate until 22 different tools that are automatically changed and average time between tool changes was stated by manufacturer as approximately 11 seconds.

The SURFCAM software was used to control and implement machine tool parameters, as the tool type, the tool path, the number of steps and the machine spindle rotation. This software may also apply simulation of the processing before the final processing code is transferred to the CNC machine. The first step was converting the parasolid format of data file by *open* command, and the CAD model was showed at the computer screen. The required volume of the material was defined by the command *create/line/rectangle* that presented a 185 x 50 x 50 mm region, equivalent to the material block used to machine the surface. The control of machine tool parameters was performed by the *operation manager* window, according to the following description.

Using menu *setup one*, the first step is the selection of the created rectangle, by using the command *edit setup information>stock* and selecting the *geometry Bounding Box*. The Z coordinates were adjusted for the material limits imposed and the command *Modify* is selected to save and quit. The rough machining was implemented with command *NC>3 axis>Z roght*, where the tool type, rotation, cutting speed and others were defined and the tool path was automatically created. Table 1 shows the operational steps and respective tools used to machine the part. The defined tool path may be visualized by a computational simulation on the computer screen. The commands *Z finish* and *Planar* were selected to define the pre-finishing and finishing operations. After defining the machining steps, the G-code was created to implement on the CNC machine tool. This was also accomplished with *Operation Manager menu*, selecting *ArcFltr* and *Post* in sequence, following the steps demanded by the software to define *Fanuc01* language and coordinate system *54*. The G-code was then automatically generated and a pop-up window opened showing the code. The code was saved before sending to the CNC machine tool and beginning the machining operations.

Table 1. Processing variables adjusted by SURFCAM software.

| Operation Number | Tool Number | Comments | |
|---|---|---|---|
| 1 | 18 | Operation Comments:<br>Tool Comments: | Coromant 40 mm<br>40 round insert |
| 2 | 21 | Operation Comments:<br>Tool Comments: | Coromil 10 mm<br>COROMILL 10 |
| 3 | 7 | Operation Comments:<br>Tool Comments: | Esferical - diameter 8 mm<br>8 mm - 4 flute - HSS Ballmill |

The surface was produced with an epoxy-based composite RenShape 5179 also known as Cibatool. Some properties of this material are hardness Shore D 85, tensile strength 68.9 MPa, compressive modulus 2.24 GPa, density 1.17 kg/m$^3$ and glass transition temperature (Tg) 115 $^{o}$C (Matweb, 2011). A block of this material having dimensions of 185 x 50 x 50 mm was rigidly attached at machine tool table. The CNC Machining Center was turned on and reseted by pressing the *zrn* button. The longitudinal dimension of the RenShape material was aligned with machine tool *x* axis using a dial gauge. The machine coordinate system was transferred to the RenShape block with the aid of a low speed rotative tool. When the tool makes contact with the block surface, the position was registered and adopted as the origin of the machine coordinate system. The machining program may then be loaded into the memory card of the CNC Machining Center and the manufacturing operation starts.

After manufacturing, the analysis of the CAD/CAM processing was carried out by checking the deviations found in respect to freeform surfaces investigated. The first analysis was applied to investigate the deviations between the runner measured points and the fitted CAD model. The second analysis was applied to investigate the deviations between the points measured on manufactured CAM surface and the fitted CAD model.

The deviations between CAD model and data points were carried out with Rhinoceros software, in both cases. The fitted curves were selected on the computer screen and the points were extracted by applying the command *Extract points* in the *Curves* software menu. The points were verified in respect to being considered as outliers and deleted in this case. The deviations were determined comparing the points with the CAD model using the command *Point set deviation*. Analysis was presented by plotting deviation intervals with different colors over the CAD model of the propeller and pointing the deviations with respective locations over the CAD surface. Statistical parameters as mean, median and standard deviation were determined to achieve comparisons.

## 3. RESULTS AND DISCUSSION

Data points were determined with the AACMM according to the strategy presented and NURBS curves were fitted and are presented in Fig. 2.a. The surfaces generated are presented in Fig. 2.b. The grid lines shows the mesh created by Rhinoceros to represent the freeform surface as a NURBS model. Despite of some deviations in curvature associated to the measured data points, the NURBS surface showed uniformity. This surface was achieved manually applying the CAD software tools and the deviations of data points in relation to CAD model were associated to this manual adjustment.

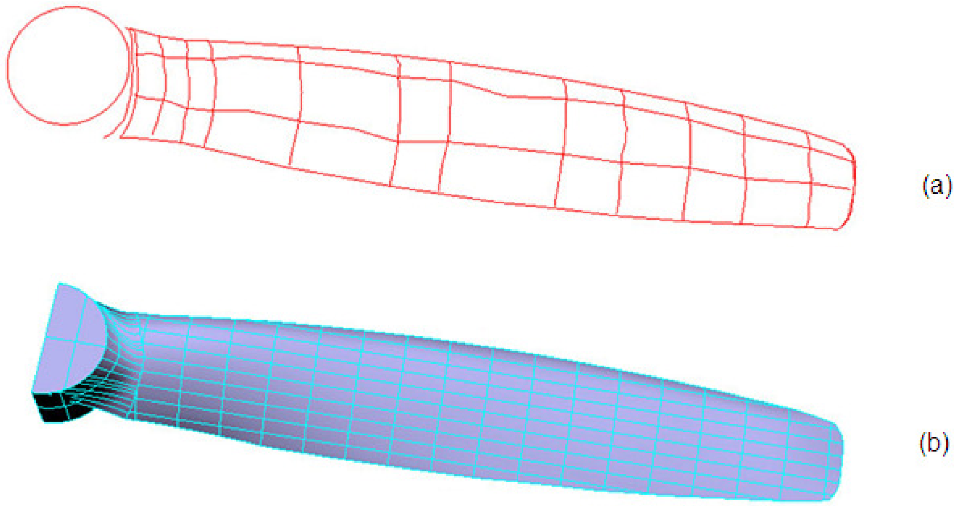


Figure 2. Measured curves (a) and resulting CAD model (b).

Figure 3 shows the paths generated by SURFCAM software to drive the machining tool. The lines represent the paths adopted to move the tool during movimentation and cutting operations. The shaded portion (blue color) indicates the runner subjected to machining. This configuration was presented by the CAM software on computer screen before cutting operations began.

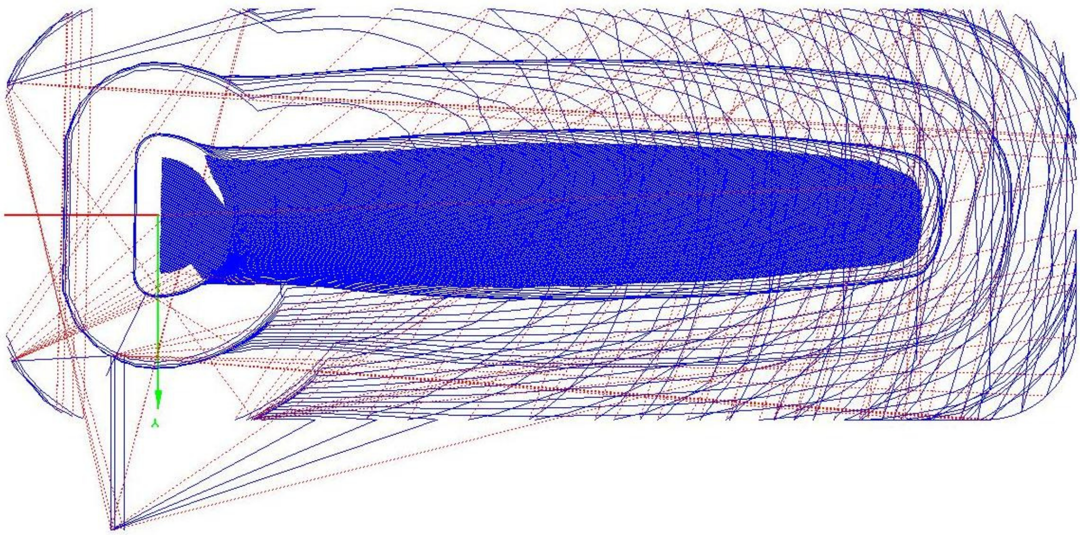

Figure 3. Ilustration of the tool path over produced surface.

The CAM processing was carried out in three steps, the rough, finish and planar operations. The processing variables were selected to reduce time spent in machining and Tab. 2 presents the feed rate, plunge rate and spindle speed adopted. The minimum and maximum coordinates in the three axis of the machine tool were presented to show the range of movimentation during the steps of processing. This configuration was saved as a G-code program having 23669 lines and it was implemented on CNC machine tool. This configuration provided a machining time of 20 minutes and 20 seconds, disregarding the time spent in changing the tools. The time spent in tool changes was about 10 seconds per tool and it was performed automatically by the machine. It was observed that planar operation was more time consuming than the rough and finish ones.

Table 2. Operations executed during machining of the freeform surface.

| Tool | Operation | Plunge Rate (mm/min) | Feed Rate (mm/min) | Spindle Speed (rpm) | Min X | Min Y | Min Z | Max X | Max Y | Max Z | Cycle Time (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | 3 Axis Z Rough | 3000.000 | 3000.00 | 4500 | -199.125 | -44.940 | 0.500 | 33.097 | 68.444 | 25.000 | 6:37 |
| 21 | 3 Axis Z Finish | 4000.000 | 5000.00 | 7000 | -170.053 | -18.626 | -3.000 | 11.295 | 34.841 | 25.000 | 3:36 |
| 7 | 3 Axis Planar | 2500.000 | 2500.00 | 6000 | -165.708 | -15.628 | -1.837 | -0.397 | 15.520 | 41.000 | 10:07 |
| Overall | | | | | -199.125 | -44.940 | -3.000 | 33.097 | 68.444 | 41.000 | 20:20 |

The machined runner surfaces with freeform geometry sculped in the material block are presented in Fig. 4. As observed, only one face was manufactured as it is enough to evaluate the processing of the freeform surface. It may be observed the gray lines scratched over the surface that were used in the subsequent measurement to perform evaluation of the CAM processing. This measurement strategy was similar is respect of the initial runner adopted measurement strategy, in which 10 points were measured along each defined transversal line using the AACMM.


Figure 4. CAM manufactured freeform surfaces.

Figure 5 presents the deviations of the measured model data points in relation to the created CAD model (complete surface). As shown, there is a large amount of points remaining in the interval between 0 and 0.1 mm (blue). Some points located at the edges presented deviations bigger than 0.1 mm, with the biggest deviations located at the connection between the runner surface and the central cylinder (values between 0.4 and 0.5 mm, red points). These values may be associated to the difficulty in positioning the AACMM probe stylus over the curved surfaces during measurement, as well as to the reduced number of points acquired that was not enough to promote a precise definition of the curvature in CAD software. It was also observed some deviations lying between 0.2 and 0.3 mm and between 0.3 and 0.4 mm at edge locations on CAD surface, and these were associated to difficulty in positioning the AACMM stylus during measurement.

Descriptive statistics of the deviations are presented in table 3. It was observed that the mean and the median of the complete surface and runner were different, implying in asymmetry of deviations distribution. It was observed that the connection surface presented the biggest mean and standard deviation in relation to the runner surface and the complete model, but the smallest median. Thus, the distribution of the deviations in the connection surface is less asymmetric. The standard deviation os the points in the connection surface (0.142 mm) was bigger than the complete surface (0.086 mm) and runner (0.063 mm).

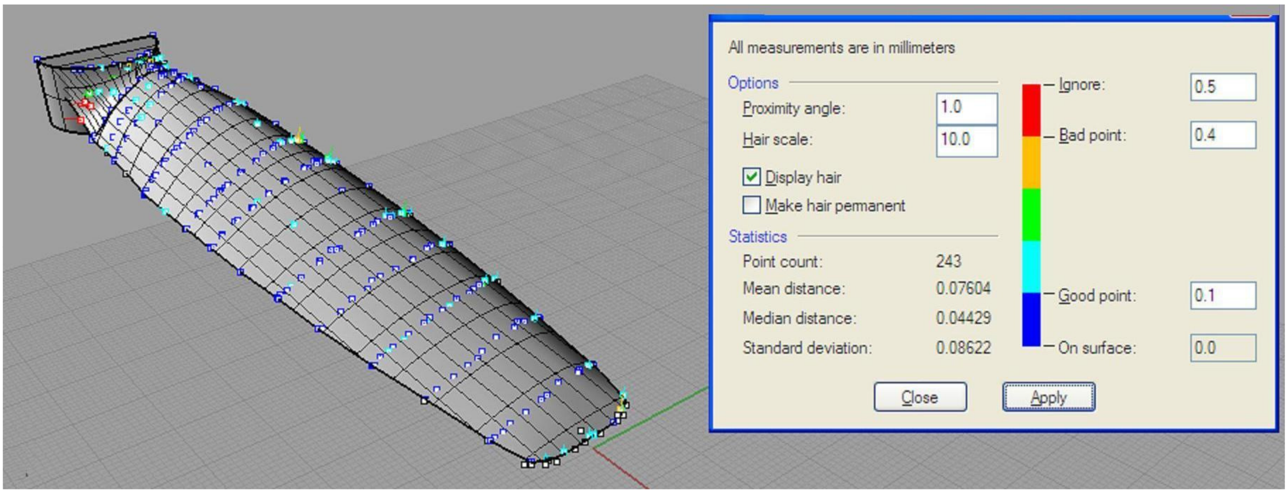


Figure 5. Deviation analysis of the CAD model.

Table 3. Data from CAD model evaluation.

| Analyzed surface | Analyzed points | Mean Distance (mm) | Median Distance (mm) | Standard deviation (mm) |
|---|---|---|---|---|
| Complete model | 243 | 0.076 | 0.044 | 0.086 |
| Runner surface | 211 | 0.062 | 0.040 | 0.063 |
| Connection surface | 32 | 0.170 | 0.015 | 0.142 |

Figure 6 shows the deviations between the CAD model and the data points determined over the CAM manufactured surfaces (complete surface). As observed, there are deviations distributed between 0 and 0.5 mm, the biggest ones lying between 0.4 mm and 0.5 mm and located at the runner edges. The mean and median were close to each other and a deviations distribution have asymmetry. As table 4 presents, the descriptive statistics showed the same behaviour of the mean and median of the runner and the connection surface, as observed to complete surface, but the standard deviation of the connection surface (0.004 mm) was reduced when compared to the complete model (0.090 mm) and to the runner (0.091 mm).

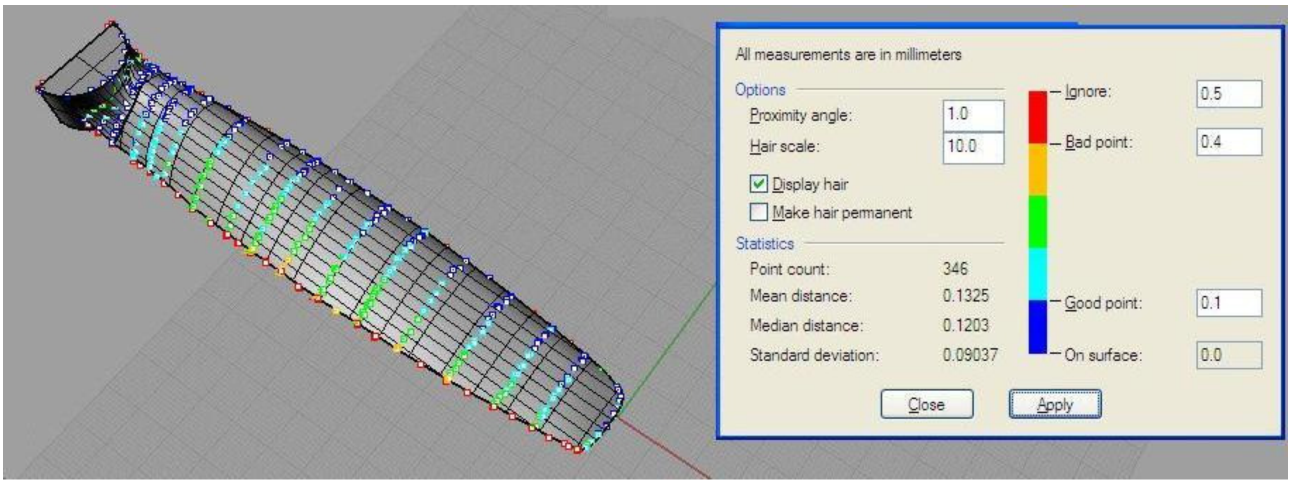


Figure 6. Evaluation of the CAM machined runner.

Table 4. Data from CAM machined part evaluation.

| Analyzed surface | Analyzed points | Mean Distance (mm) | Median Distance (mm) | Standard deviation (mm) |
|---|---|---|---|---|
| Complete model | 346 | 0.132 | 0.120 | 0.090 |
| Runner surface | 314 | 0.139 | 0.132 | 0.091 |
| Connection surface | 32 | 0.019 | 0.020 | 0.004 |

The comparison of the two analysis was performed and it is showed in Fig. 7 to the complete CAD and CAM models. As observed, the lack of symmetry is more pronounced in CAD model evaluation, as a large amount of deviations are located between 0 and 0.1 mm and the mean was 0.076 mm. This may be associated to the capability of the CAD software and NURBS modeling in fitting geometries having freeform and to the acuracy of the measuring machine. On the other hand, the deviations of the CAM machined surfaces were more scattered through the adopted groups of deviations and presented a mean of 0.132 mm. This may be associated to the limitations and to the geometrical errors of the three-axis CNC machine used. The standard deviation in both cases were closer, as CAD was 0.086 mm and CAM was 0.090 mm.

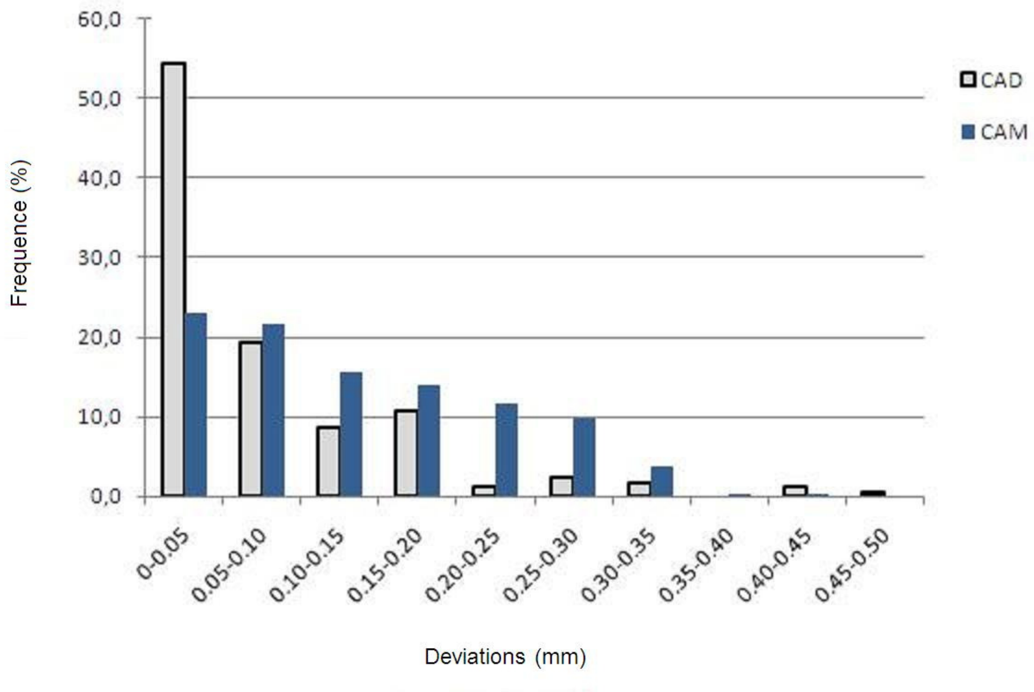


Figure 7 – Analysis of deviations between points on runner prototype (CAD) x CAD model and points on manufactured runner (CAM) x CAD model.

## 4. CONCLUSIONS

The CAD/CAM processing of freeform surfaces was studied through measurement and manufacturing of a propeller runner. The accuracy and repeatability of CAD and CAM processing steps was verified by calculating the deviations between the measured points on part surface and CAD fitted model (CAD analysis) and between the measured points on CAM machined surface and CAD fitted model (CAM analysis).

The CAM manufactured surface presented bigger deviations than CAD ones, having a mean of 0.132 mm (CAM) against 0.076 mm (CAD). The CAM associated standard deviation was 0.090 mm and it was close to the CAD standard deviation 0.086 mm. The deviations distribution was asymmetric in both cases, but a more pronounced asymmetry was observed in CAD analysis. This may be associated to the capability of CAD and NURBS modeling in fitting data points to surfaces and to the limitations and geometric errors of the CNC machine tool used.

An analysis of a small freeform surface was accomplished using the connection surface of the propeller. CAM processing generated this surface with a mean of 0.019 mm and the CAD mean was 0.170 mm, while the CAM standard deviation was 0.004 mm and CAD standard deviation was 0.142 mm. These differences in relation to the freeform complete model may be explained by the accuracy of CAM processing at localized volumes as the machining tool may generate this profile with a simple or a few machining rides.

In an attempt to increase accuracy and repeatability, other techniques may be used to carry out the measurements, as non-contact optical devices and laser probes coupled with CMMs. The use of CNC machine tools having 5-axis may be investigated to improve accuracy and repeatability of the manufactured parts.

## 5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Fundação de Apoio à Pesquisa do Distrito Federal – FAPDF by financing this work.

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