Reverse engineering of hydraulic turbine runners using coordinate measuring arms and NURBS modeling

Antonio Piratelli-Filho
antonio.piratelli@yahoo.fr
Universidade de Brasília

José Alexander Araújo
alex07@unb.br
Universidade de Brasília

Antonio C.P. Brasil Júnior
brasiljr@unb.br
Universidade de Brasília

Resumo

Este trabalho apresenta uma metodologia para construção de modelos de Projeto Auxiliado por Computador (CAD) de peças de grande porte e com geometria complexa, como as pás de turbinas hidráulicas. A metodologia foi desenvolvida aplicando técnicas de engenharia reversa e modelagem com B-splines racionais não-uniformes (NURBS). Uma estratégia de medição foi proposta para reconstrução do modelo CAD de uma pá de turbina hidráulica Kaplan e as medições foram feitas na Usina Hidrelétrica de Coaracy Nunes, no estado do Amapá, Brasil. Uma turbina Kaplan com diâmetro 4,3 m foi medida com uma Máquina de Medir por Coordenadas modelo braço articulado (CMA), usando uma sonda rígida com contato. Amostras de pontos com coordenadas das superfícies foram obtidas e armazenadas em arquivo de computador. Os modelos CAD foram construídos usando técnicas de modelagem com NURBS e a análise dos erros foi feita comparando os pontos medidos com os pontos equivalentes das superfícies CAD. Os resultados mostraram que a metodologia propiciou o desenvolvimento de modelos CAD com erros de pequena magnitude, adequados para aplicações de simulação computacional de escoamanento de fluidos e análise de tensões.

Palavras-chave: Engenharia reversa. Superfícies de forma livre. Medição de rotores de turbinas hidráulicas.

Abstract

This work intends to address the issue of Computer-Aided Design (CAD) model development associated to large complex geometries like hydraulic turbine runners, applying reverse engineering techniques and Non-Uniform Rational B-Splines (NURBS) modeling. A measurement strategy was proposed to reconstruct a Kaplan hydraulic turbine runner. The experimental approach was developed at Coaracy Nunes power plant, pertaining to Eletronorte and located in Amapá state, Brazil's north region. A turbine runner having 4.3 meters long was measured using a Coordinate Measuring Arm (CMA) with contact probe and samples with point coordinates of the runner were obtained. The CAD models were built using Non-Uniform Rational B-Splines (NURBS) modeling techniques and error analysis was performed comparing data points with respective CAD points. The results showed that the methodology proposed generated low error CAD models that are suitable to future engineering development using computational simulation.

Keywords: Reverse engineering. Free form surfaces. Hydraulic turbine runner measurement.

1 Introduction

Nowadays, refurbishment of hydraulic turbine runners is being under evidence as there is a need of improvement of electric power generation in power plants under operation in Brazil. Improvement may be obtained through operational protocol analysis and maintenance tasks, power plant inspection, execution of performance tests and redesign of hydraulic turbine runners. The redesign process involves changing the original geometry and dimensions of any part based on computational simulations performed with the computer-aided design (CAD) model. This procedure may require field measurements to acquire the geometry and dimensions of the runner and hydraulic machine and the search for an appropriate CAD model.

The runner is an example of large part having free form surfaces that are designed to obtain the best performance with water flowing across the turbine. These types of surfaces are being increasingly used when functional aspects and esthetics are required, as advanced fabrication processes having superior precision are nowadays available. Advances in fabrication techniques have been requiring the development of new methods and equipments for measurement and inspection of complex free form surfaces (BAGCI, 2009).

Reviewing the methods used to inspect turbine runners, it was observed that three main techniques are carried out: templates, laser tracker and Coordinate Measuring Machines (CMM). The method using a CMM is recommended as it demands short period of time to be executed than templates and it results in reduced cost in relation to laser tracker. It is still possible to adapt a non contact probe on CMM to reduce the time spent in measurement, but there are drawbacks associated to environmental conditions in the power plant like high humidity and temperature that can affect accuracy of the results (DUMOULIN *et al*., 1994).

Dumoulin *et al.* (1994) presented a methodology to recover the design of a Francis hydraulic turbine runner. The authors had compared the three methods presented to carry out the measurements in field location and concluded that using an articulated arm CMM (Coordinate Measuring Arm or CMA) generated better results than using laser tracker and templates. Some difficulties were found related to the measurement strategy and the sample size, as it was necessary to define a path and a sequence to take points on the surface using a rigid type probe and to define the number of points on surfaces to carefully reproduce the curvature and profile.

The measurement of turbine runners are performed according to the following steps: positioning and preparation of the CMA, determination of a reference position on the part surface, determination of point coordinates on the surfaces, storing data in computer files, changing file to a CAD compatible and readable file format, rebuilding the geometry in computer and comparison of the results with the tolerances specified by design. This sequence is used to improve the design of an existent turbine runner through the application of computational simulation methods with the CAD models recovered to investigate the effect of geometry modifications over the hydraulic machine performance (DUMOULIN *et al*., 1994).

The main error sources related to this process of measurement may be pointed out as the sampling strategy and the compensation of stylus probe radius. Ip and Loftus (1996) presented a technique to compensate the radius of the probe stylus when measuring a free form surface with a CMM. Cho and Kim (1995) developed a measurement strategy based on the curvature analysis of the free form surfaces and an approach to optimize the distribution and the sequence of the determined points.

An important issue when measuring with CMMs is the traceability of the results. As well known, the essential condition to obtain traceable results in a measurement is that the instrument must be calibrated. Nevertheless, CMMs are machines that determine points on a part surface in a given work volume having an infinite number of points. Thus, a calibration method should give the possibility of verify all points and establish the measurement uncertainty. Some methods used to evaluate the errors on CMMs are limited to check the performance of the machine as only limited number of positions and orientations are investigated with gauges (PIRATELLI-FILHO and GIACOMO, 2003). A calibration approach well accepted is the virtual CMM and it is used to determine the uncertainty of any measurement performed (TRAPET *et al.*, 1999; SCHWENKE *et al.*, 2008). The virtual CMM approach was developed by mathematical modeling of all error sources of the machine and it is in agreement with the ISO Guide to the Expression of Uncertainty in Measurement (ISO GUM, 1995).

In this work, a methodology to recover a Kaplan hydraulic turbine runner is proposed. It involves the measurement of Kaplan runners using a Coordinate Measuring Arm machine with contact probe and the development of CAD models using Non-Uniform Rational B-Splines (NURBS) modeling techniques. The error analysis was carried out comparing the data points with the respective CAD points.

2 Kaplan turbine runner and measurement methodology

A Kaplan turbine runner is a type of runner having adjustable blades and it is used to generate electric power from water flowing into the hydraulic turbine cavities. The water pushes the blades and causes a spinning movement of the runner around the turbine axis. The surfaces of a Kaplan turbine runner must have a curved geometry as a way to maximize the rotation and the power generation and engineering research are under development to implement form modifications on its surfaces to improve power generation.

The first issue in building a CAD model of a part with unknown design geometry and dimensions deals with the acquisition of the profile and the contour of the surfaces with good agreement to the real surface. There are several error sources that can cause bias in the determined data points, as temperature changes and humidity among others, and it is required a robust procedure to minimize their effect. When involving field measurements, the equipment selected must be portable to easy transportation to the location where the measurement will take place. Data must be stored in data files to subsequent construction of the CAD models.

Information about design of turbine runners is demanded to select the instrument and the method to carry out the measurements. According to the standard IEC 60193 (1999), the tolerances of the design parameters like nose and blade runner profile and thickness, are function of the runner diameter. The tolerances of the blade surface profiles are specified as ± 0.1 % D, where D is the runner diameter. As the turbine runners under operation at the select power plant was 4.3 m, the tolerance is 4.3 mm and it is required a measurement instrument having an uncertainty smaller than 0.43 mm.

Among the methods presented, the most suitable to the required measurement conditions and accuracy demanded is the Coordinate Measuring Arm (CMA). Thus, a CMA manufactured by Romer, ARM 100 model, having an arm reach of 2.5 m was used to carry out measurements. This instrument, having 6 degrees of freedom, has an accuracy of 0.07 mm and is connected to a portable computer to control the measurement tasks and the data acquisition. It was used a hard probe to determine points on the surfaces, having a rigid stylus with small curvature tip. The transformations of angles determined at each articulation encoder to Cartesian coordinates were done by the software G-Pad, as well all data processing. The total weight of the machine and computer was 12 kg, providing easy transportation to field location.

The experimental procedure adopted was developed to measure and build the CAD model of a Kaplan type turbine runner. This runner was installed and operating at Coaracy Nunes power plant, located at Ferreira Nunes city, Amapá state, Brazil. The methodology may be extended to other types of turbine runners with some adaptations.

The measurements took place at Coaracy Nunes power plant with help of Eletronorte operational staff during the changeover of the runner due to an upgrade of the machine. Two turbine runners of Kaplan type where measured and the first named K1 and the other K2. The K1 was under operation during almost 30 years and had an apparent modified geometry in relation to the K2 that was being prepared to enter in operation. Both runners were located at the site and facilities where available to begin measurements.

Prior to measurements, lines were drawn on both blades surfaces to represent the measuring directions and positions were points must be captured, as shown in Figure 1. The number of points required was determined by experience, considering the number of segments having different curvature or form and the order of the resulting curve. As it is well known, high order curves demands a higher number of points than low order ones.

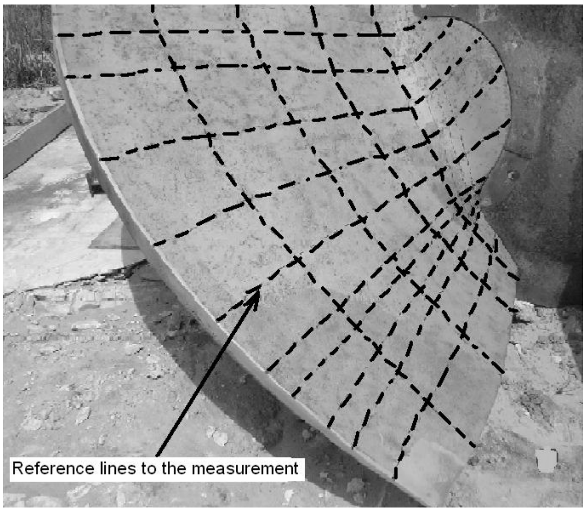

Figure 1: Lines defining the sequence of measurement on a Kaplan turbine blade.

The CMA was positioned on the metallic blade surface by using its magnetic basis (support). A notebook was then connected to the CMA to control the process of taking points by software. An operator manipulated the arm probe searching for the previously established marks locations on the blade surface, as showed in Figure 2.

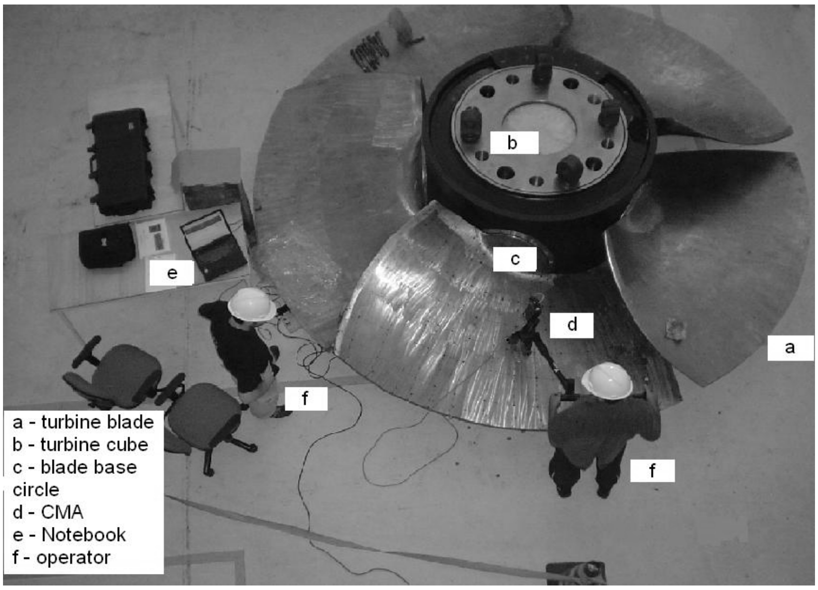

Figure 2: Measuring a Kaplan turbine runner with CMA.

The first measured turbine runner was the K1 and it was measured two blades of the runner. Each blade was measured after tracing a grid of lines that gives a route to perform the measurement task. It was designed 13 lines in radial direction on each blade surface having 9 or 10 points along each line, performing 26 lines per blade. Besides, the blade contour was measured taking 39 points at first blade and 38 points at second blade, fitting a polyline to the group of points as a frame reference. The total number of points for these two blades was 498 (243 for the first and 255 for the second blade). It was also measured the base circles of each blade and the base circle of the runner by determining 9 points at each one. The profile of the runner body was determined taking 22 points along its curvature in a plane parallel to its revolution axis. The time spent in measurement was 40 minutes and the time spent in the runner positioning and in the measuring system installation was nearly the same. Figure 3 shows data obtained after measurement.

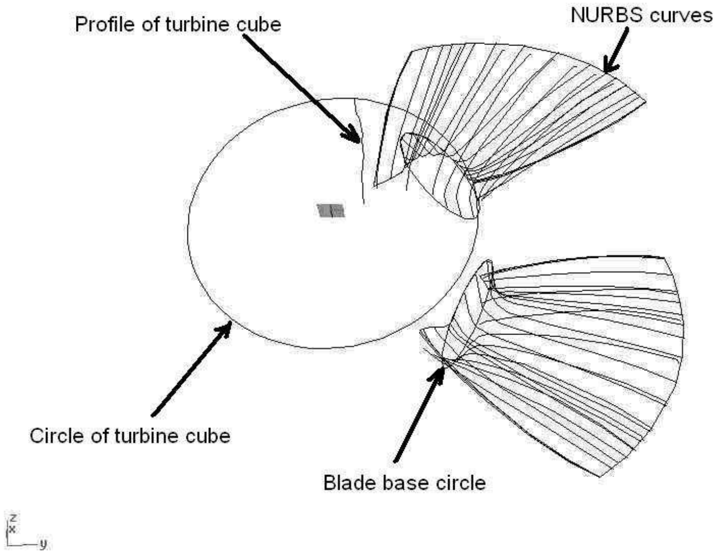

Figure 3: Curves obtained with measurement of K1 Kaplan turbine runner.

The measurement of the K2 Kaplan turbine runner was carried out determining profiles and surfaces at one blade, using the same approach as for the K1 runner. In this setting, it was traced 16 radial lines on the upper blade surface and 17 lines on the lower surface, taking 10 points at each line with the CMA. The total number of points determined was 330 by blade. The blade contour was determined with 41 points and a reference frame was built. The basis circle of the runner was determined taking 9 points and the profile of the runner body was determined taking 12 points. Figure 4 shows these results.

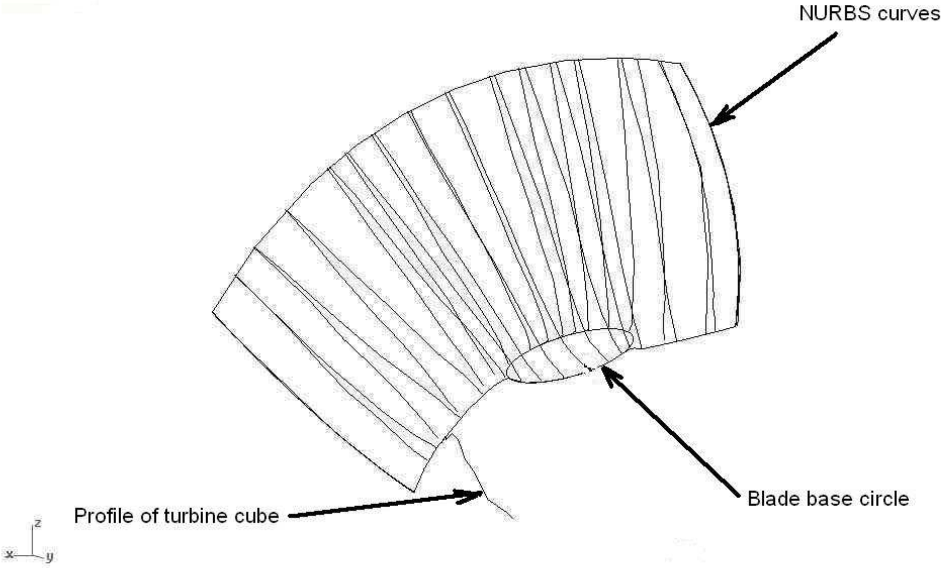

Figure 4: Curves obtained through measuring the K2 Kaplan turbine runner.

3 NURBS curves and error analysis

Data obtained by measurement with CMA was then fitted to Non-Uniform Rational B-Splines (NURBS) curves and surfaces. Figure 5 shows the path followed to fit data points using CAD software, beginning with measurements on a CMA up to simulations using engineering software. It should be noted that files in format IGES (Initial Graphics Exchange Specification) were used, since this is a common format used by many CAD software like Catia, Rhinoceros and SolidWorks to convert data from measuring machines.

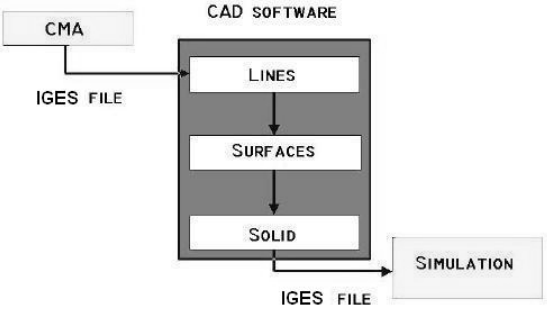

Figure 5: Data processing steps from measurements to simulation.

NURBS are defined as vector-valued piecewise polynomial functions and the equations of curves and surfaces are showed by Equations 1 and 2 respectively (LIU *et al.*, 2006; PIEGL and TILLER, 1997).

$$C(u) = \frac{\sum_{i=0}^{n} P_i \cdot w_i \cdot N_{ik}(u)}{\sum_{i=0}^{n} w_i \cdot N_{ik}(u)} \tag{1}$$

$$S(u,v) = \frac{\sum_{j=0}^{m}\sum_{i=0}^{n} P_{ij} \cdot w_{ij} \cdot N_{ik}(u) \cdot N_{jl}(v)}{\sum_{j=0}^{m}\sum_{i=0}^{n} w_{ij} \cdot N_{ik}(u) \cdot N_{jl}(v)} \tag{2}$$

In these equations, P_i and P_{ij} are the control points, w_i and w_{ij} are the weights attributed to the control points, k and l are the degrees of the curves in the directions u and v, n and m are the number of control points in the directions u and v. The function $N_{ik}(u)$ is the basis function defined by B-spline function and it is determined by Equations 3 and 4. The values u_i are the ith element of the knot vector U, defined by Equation 5. The function $N_{jl}(v)$ is determined by the same equations, changing i, k and u by j, l and v. The same considerations to knot vector U applies to knot vector V, defined by Equation 6.

$$N_{i,0}(u) = \begin{cases} 1 & if\ u_i \le u \le u_{i+1} \\ 0 & otherwise \end{cases} \tag{3}$$

$$N_{i,k}(u) = \left(\frac{u - u_i}{u_{i+k} - u_i}\right) \cdot N_{i,k-1}(u) + \left(\frac{u_{i+k+1} - u}{u_{i+k+1} - u_{i+1}}\right) \cdot N_{i+1,k-1}(u) \tag{4}$$

$$U = \left\{ \underbrace{a, \dots, a}_{k+1}, u_{k+1}, \dots, u_{m-k-1}, \underbrace{b, \dots, b}_{k+1} \right\} \tag{5}$$

$$V = \left\{ \underbrace{c, \dots, c}_{l+1}, v_{l+1}, \dots, v_{n-l-1}, \underbrace{d, \dots, d}_{l+1} \right\} \tag{6}$$

The data processing involved adjustment (approximation) of NURBS curves following the measurement paths. This means that the curves do not cross exactly over the data points and there are errors related to the fitting procedure. Least squares method was used to minimize these fitting errors (PIEGL and TILLER, 1997).

The CAD NURBS surface models were established to each entity investigated. Error analysis involved the determination of the distances between surfaces models and data points and Rhinoceros software was used to perform the calculations.

Turbine runners were built fitting NURBS curves and surfaces to the data on each blade side. Secondary surfaces were built at edges and vertexes of the blade surfaces to join the suction and pressure surfaces on each blade. For K1 runner, after fitting the two measured blades, three additional blades were obtained copying the best fitted blade and reproducing it along the curvature of the runner basis circle. The resulting NURBS surface may be observed at Figure 6.

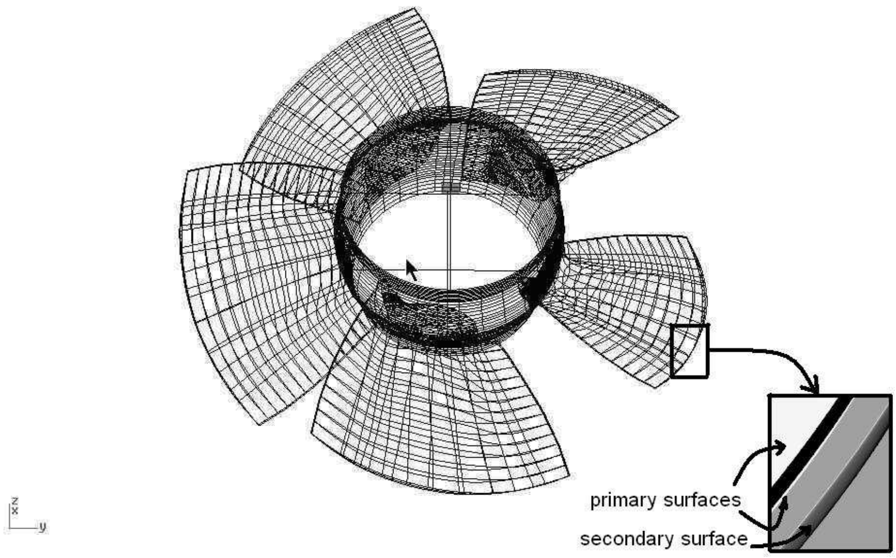

Figure 6: CAD model of the K1 Kaplan turbine runner.

The data processing of the K2 turbine runner was carried out according to the same procedure implemented to the K1 runner. Therefore, four additional blades were drawn based on the measured and fitted one. Figure 7 shows the complete NURBS surfaces and CAD model of the K2 turbine runner obtained by the proposed methodology.

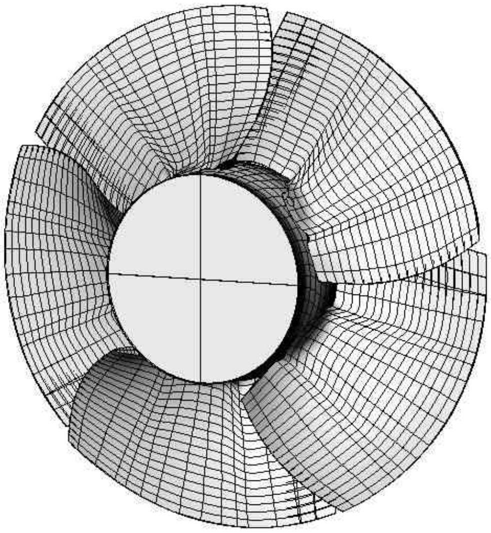

Figure 7: CAD model generated to the K2 Kaplan turbine runner.

The time spent to measure each blade surface on K1 runner was 40 minutes, in opposition to the K2 were one hour was necessary. Preparation to perform measurement required one hour for K1 and K2 runners, time associated to cleaning the surface, drawing a net on the blades surfaces to capture points coordinates and equipment installation. Therefore, the whole process gives a total time of 2 hours and 20 minutes for K1 runner and 2 hours for K2 runner.

Error analysis of the K1 turbine runner CAD model was carried out comparing the distance between measured points and the corresponding ones at the model, as showed in Figure 8. As we can verify, a large amount of points (more than 99%) was comprised in a tolerance zone having 4 mm width. It was observed that the greatest errors (between 4 and 5 mm) were located at secondary surfaces near the edges and the vertexes of principal surfaces and near the runner basis body. The curvatures at these regions may be refitted to reduce the errors, editing NURBS surfaces to make them closer to the data points.

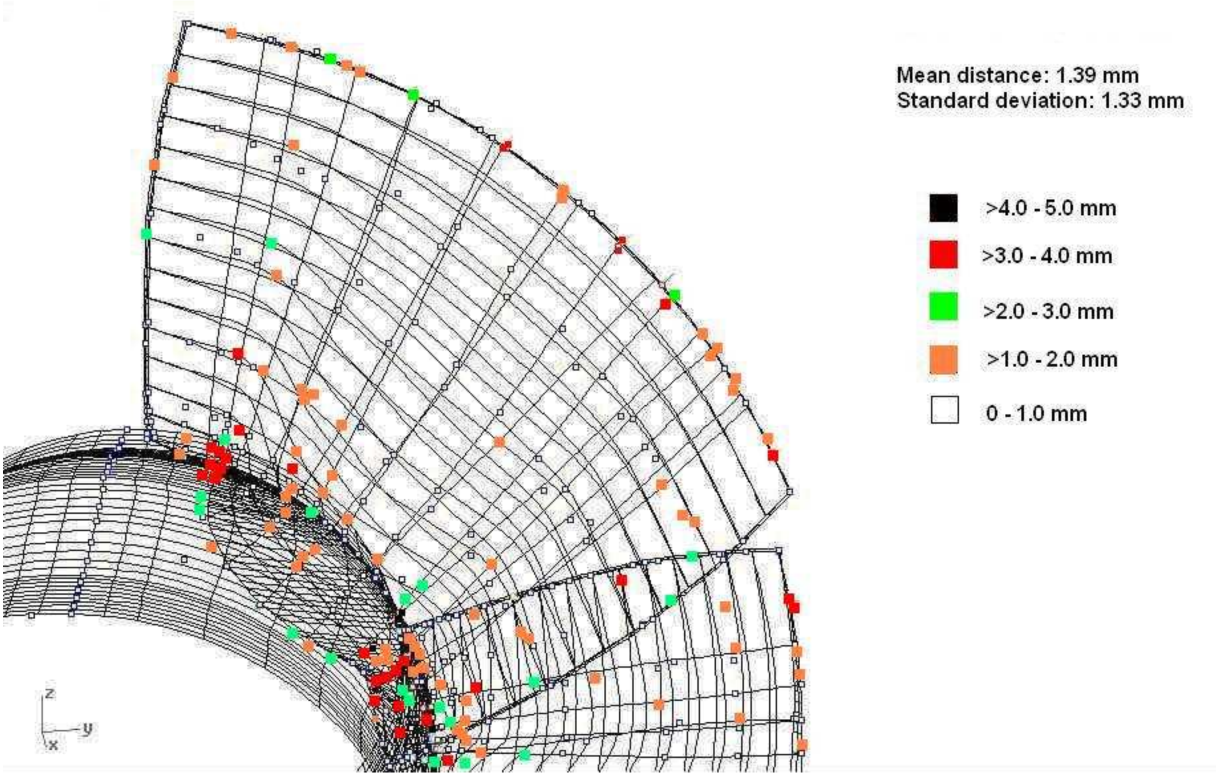

Figure 8: Error analysis of CAD model of K1 Kaplan turbine runner.

Error analysis of the K2 turbine runner CAD model was carried out and Figure 9 shows the results. It can be observed that there are a large amount of data points having errors smaller than 1 mm. There were some points located at edges and vertexes that presented errors greater than 5 mm (8 points in 330). As observed at K1 Kaplan turbine runner, secondary surfaces at edges and vertexes may be edited to reduce errors, if required.

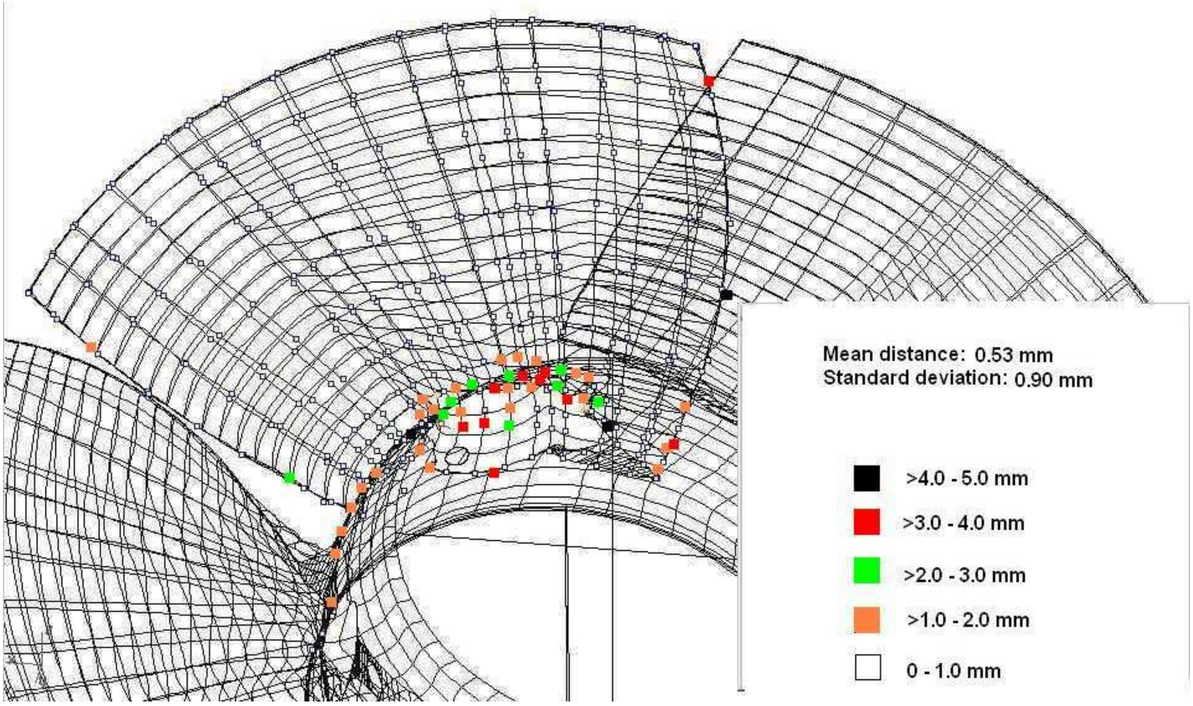

Figure 9: Error analysis of the CAD model of the K2 Kaplan turbine runner.

4 Conclusion

A methodology developed to measure Kaplan hydraulic turbine runners was implemented to create CAD models based on a measurement strategy to acquire points on the surfaces and algorithms to fit data points to curves and surfaces. The measurement strategy involves fixation of the CMA on the surfaces of the blade runner, tracing a grid of lines on the blade surface to define the number of points to measure and defining the sequence and direction of measurement. Curves and surfaces were fitted using low degree polynomials known as NURBS.

The methodology was used to build CAD models of the Kaplan hydraulic turbine runners of Coaracy Nunes power plant in Amapá state, Brazil's north region. A comparison was conducted regarding deviations in blade geometry and dimension relative to the generated CAD models. These deviations called errors in relation to CAD models were smaller than 5 mm on the blade profiles at K1 and at K2 runners. These values were of small magnitude when compared to dimensions of the runners, about 4300 mm in diameter. The time spent in measurement was at the same level of the time spent in preparation to measure, involving positioning and fixation of the machine and tracing grid of lines on blade surface.

Future work may involve adjustment of the developed methodology to reconstruction of another model of turbine runners, like Francis type. Besides, a rigorous evaluation of the error sources may improve the CAD model fitted.

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References

BAGCI, E. Reverse engineering applications for recovery of broken or worn parts and re-manufacturing: three case studies. *Advances in Engineering Software*, v. 40, p. 407-418, 2009.

CHO, M. W.; KIM, K. New inspection planning strategy for sculptured surfaces using coordinate measuring machine. *International Journal for Production Research*, v. 33, p. 427-344, 1995.

DUMOULIN, C.; AVELLAN, F.; HENRY, P. Geometry recovery of a francis runner prototype at site. In: IAHR SYMPOSIUM, 17., 1994, Beijing. *Proceedings...* Beijing: Association of Hydraulic Engineerring and Research, 1994. v. 3, p. 1125-1136.

INTERNATIONAL ELECTROTECHNICAL COMISSION. *IEC 60193 STANDARD*: hydraulic turbines, storage pumps and pump-turbines: model acceptance tests. Geneva, 1999.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. *Guide to the expression of uncertainty in measurement.* Geneva, 1995.

IP, W. L. R.; LOFTUS, M. Adaptive and compensation methods in free-form surface assessment. *Journal of Engineering Manufacturing*, Boston, v. 210, p. 135-145, 1996.

LIU, C. et al Micro stereo matching based on wavelet transform and projective invariance. *Measurement Science and Technology*, v. 17, p. 565-571, 2006.

PIEGL, L.; TILLER, W. *The NURBS book.* 2nd ed. Berlin: Springer, 1997. 646 p.

PIRATELLI-FILHO, A.; GIACOMO, B. D. CMM uncertainty analysis with factorial design. *Precision Engineering*, v. 27, p. 283-288, 2003.

SCHWENKE, H. et al. Geometric error measurement and compensation of machines: an update. *CIRP Annals - Manufacturing Technology*, v. 57, p. 660-675, 2008.

TRAPET, E. et al. *Traceability of coordinate measurements according to the method of the virtual measuring machine*: final project report MAT1-CT94-0076 PTB-Bericht F-35. Braunschweig: Physikalisch-Technische Bundesanstalt, 1999. Part 1 and 2.

SOBRE OS AUTORES

Antonio Piratelli-Filho
Engenheiro de Produção Mecânica, Universidade de São Paulo, USP – São Carlos. Mestre em Engenharia de Materiais, Universidade Federal de São Carlos – UFSCar. Doutor em Engenharia Mecânica, Universidade de São Paulo, USP – São Carlos. Professor Adjunto do Departamento de Engenharia Mecânica, Faculdade de Tecnologia, Universidade de Brasília, UnB.

José Alexander Araújo
Engenheiro Mecânico, Universidade Federal de Uberlândia – UFU. Mestre em Engenharia Mecânica, Universidade de Brasília, UnB. Doutor em Engenharia Mecânica, University of Oxford, Inglaterra. Professor Adjunto do Departamento de Engenharia Mecânica, Faculdade de Tecnologia, Universidade de Brasília, UnB.

Antonio C.P. Brasil Júnior
Engenheiro Mecânico, Universidade Federal do Pará. Mestre em Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro – PUC / RJ. Doutor em Engenharia Mecânica, École Centrale de Lyon, França. Professor Adjunto do Departamento de Engenharia Mecânica, Faculdade de Tecnologia, Universidade de Brasília, UnB.

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