MEASUREMENT OF KAPLAN HYDRAULIC TURBINE RUNNERS USING COORDINATE MEASURING ARMS

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ABSTRACT: *The aim of this work is to present an approach to measure Kaplan turbine runners using a Coordinate Measuring Arm (CMA). Different methodologies to conduct such measurement as templates and laser tracker are mentioned and discussed in literature. It was evaluated that the use of the Coordinate Measuring Arms system to measure Kaplan turbine runners is more suitable than the aforementioned ones due to its reduced cost, little time spent in measurement and facility of data processing. A prototype turbine runner is constructed and the measurement strategy, the sample dimension and data processing are studied and carried out using Rhinoceros and SolidWorks software. The measurement strategy developed has proved to be successful and the Computer Aided Design (CAD) model obtained has shown useful to simulation studies under investigation.*

Key words: *coordinate measuring machines, free form surfaces, hydraulic turbine runners*

1. INTRODUCTION

The increase in electric power generation is a challenge that has been taking place nowadays in Brazil. One approach to address this question is to upgrade the performance potential of existing hydraulic power plants through redefining geometry of turbine runners. This task requires the acquisition of turbine parts geometry using measurement methods and changing their dimensions and form to increase power generation. There is a research project under development at University of Brasilia in partnership with Eletronorte to investigate this issue.

Within the components of a hydraulic turbine, turbine runners are one of the biggest and may be considered as having free form surfaces. These free form surfaces are designed to provide the maximum efficiency during operation when water flows into turbine and its modification may be carried out starting from runner design. As the majority of power plants in operation have an advanced age, it is necessary to employ measurement techniques to recover the turbine runner design.

There are a number of methods such as templates, laser tracker and Coordinate Measuring Arms (CMA), which have been considered to measure these turbine runners. The CMA method has been reported as the more suitable one to perform measurement tasks in turbine runners since it minimizes the time spent in inspection and the costs involved (Dumoulin et al., 1994). The use of non-contact measurement techniques is disturbed due to some specific environmental conditions like those occurring in power plant turbine location, as high humidity rate and temperature.

Templates are used tracing lines in two directions over the surface to be measured. A disk with known diameter containing a pen fixed in the center is rolled over the surface in desired direction. Films with theoretical profiles of the blades are positioned in a fixed board and the pen records the real profile. Accuracy is reported as 2 mm. Laser interferometer is high cost equipment that uses laser beam light to measure positions in space. A retro-reflector is moved along different paths and the incident beam light is reflected returning to control unit. The length is determined by interferometric principles and two encoders measure the two angles, establishing a spherical coordinate system. Accuracy is reported as 0.07 mm (Dumoulin et al., 1994).

Dumoulin et al. (1994) described an approach to recover Francis hydraulic turbine runners. These authors performed a comparison among measurement methods in a power plant location and had concluded that using CMA is advantageous compared with laser tracker and templates. Magnam and Pastorel (2000) described the measurement of Francis turbine runners and discussed the steps required to process data on Computer Aided Design (CAD) software. Some difficulties when measuring free form surfaces with Coordinate Measuring Machines (CMM) were pointed out by some authors as definition of measurement strategy, sampling strategy and size (Cho and Kim, 1995; Chung, 1999; Thompson et al., 1999).

The measurement task using CMA involves the following steps: (i) positioning and fixing the CMA in turbine runner, (ii) determining a reference position in the piece, (iii) measurement of several coordinate points on surface, (iv) storing data in a Computer data file and (v) redesigning the runner in a Computer Aided Design (CAD) software. Runner surface modifications are then performed after computational simulation to improve the water flow in turbine (Dumoulin et al., 1994; Magnam and Pastorel, 2000).

In respect to error sources involved in the measurement procedure, Cho e Kim (1995) had proposed a strategy to measure free form surfaces based on curvature analysis. They suggested a criterion to optimize the distribution and ordering of measured points. Another question, which deserves more attention refers to the traceability in measurement, since there are a limited number of references in literature to test performance of CMAs (Kovac and Frank, 2001). A largely accepted approach is the virtual Coordinate Measuring Machine (CMM), where all cinematic errors of a CMM is determined and a mathematical model is constructed, which is capable to predict the machine uncertainty of any position in work volume (Wilhelm et al., 2001). A new approach proposes the application of Design of experiments methods to execute performance tests (Piratelli-Filho e Giacomo, 2003).

This work presents a methodology to measure Kaplan turbine runners using Coordinate Measuring Arms. The method have some advantages over others such as the laser tracker and templates, since it presents a reduced cost, smaller time spent in measurement and greater facility of data processing. A prototype turbine runner is investigated and the measurement strategy, the sample dimension and data processing are studied and carried out using Rhinoceros and SolidWorks software.

2. MEASUREMENT OF KAPLAN TURBINE RUNNER

As well known, the choice of appropriate measurement instrument is a function of the part tolerances. It must emphasized that Kaplan turbine runners may be designed according to the standard IEC 60193 (1999) and fabrication tolerances of the runner profiles are established as a function of runner diameter. This standard establishes the tolerance as ± 0.1% of the runner diameter (D) and specifies tolerances of some other geometry elements as runner nose, maximum runner thickness, runner thickness near outlet face and maximum plate angle.

A pilot power plant established by Eletronorte to the development of refurbishment methodology was Coaracy Nunes in Amapá State, Brazil. The turbine in operation is a Kaplan model with total diameter of 4.3 meters and with five runners of dimensions of about 2 x 2.5 meters. Thus, according to IEC 60193 (1999), the form tolerance of the runner plate must be stated as ± 4.3 mm and the maximum measurement uncertainty of the instrument to be selected is 0.43 mm.

It was selected a Coordinate Measuring Arm (CMA) model Arm 100, produced by Romer, France, to perform the measurements. This CMA has three arm segments with encoders in each joint, performing six degrees of freedom. The arm has a spherical reach of 2.5 meters and a measurement uncertainty of 0,07 mm. A rigid probe is fixed at arm termination and data is acquired by touching the measurement surface and pushing a button on the probe. Data angular information obtained at encoders is processed in a G-Pad software and transformed in rectangular coordinates and lengths. Figure 1 shows this CMA positioned over a cast iron measurement table in the Laboratório de Metrologia at Universidade de Brasília. The total weight including the notebook Computer is 12 kg and it is suitable to perform the measurements at plant location.

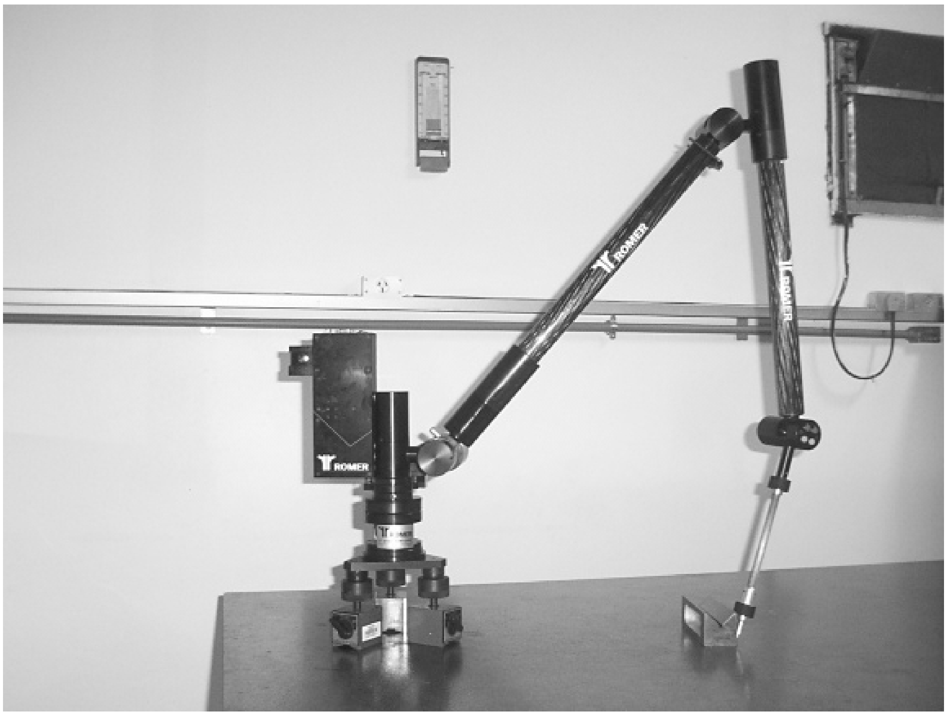

Figure 1 – Coordinate Measuring Arm

In order to develop and test the measurement methodology, a prototype of a Kaplan turbine runner, similar to the one located at Coaracy Nunes power plant, was constructed (Fig. 2). The structure was made in steel bars and a layer coat of epoxy resin was applied over Paris plaster as a finalization step. The mechanical integrity of this prototype proved to be sufficient to the development of such methodology. The measurements were performed at laboratory environment.

To measure the Kaplan turbine runner prototype, we fixed the CMA on a horizontal support so that it was possible access each one of its free surfaces at a time. A needle tip probe was used to touch the runner surface acquiring one point at a time. Point coordinates were determined along lines traced over the runner surface. The number of points measured and the direction of measurement were modified to investigate the measurement strategy. Since the arm reach is limited to one surface, the runner second surface was measured applying the *leap frog* technique, e.g.

measuring any non-collinear three points twice, with the CMA placed in two different positions. Lines were adjusted with point coordinates on G-Pad software using splines option.

Figure 2 – Kaplan turbine runner prototype

Data processing is summarized in Fig. (3). As shown, data obtained at CMA is exported in IGS format file. A CAD software is then used to create a solid Kaplan turbine runner. The design of the turbine runner was constructed using both Rhinoceros and SolidWorks software. The surfaces were obtained applying the Rhinoceros *loft* command on lines adjusted with point coordinates, creating a smooth surface that blends between selected shape curves. The solid was finally obtained applying *loft* command on surfaces using SolidWorks software, blending the selected surfaces in a solid model. The CAD model was exported in IGS format so that a computational fluid dynamic analysis can be carried out for other researchers involved in the project.

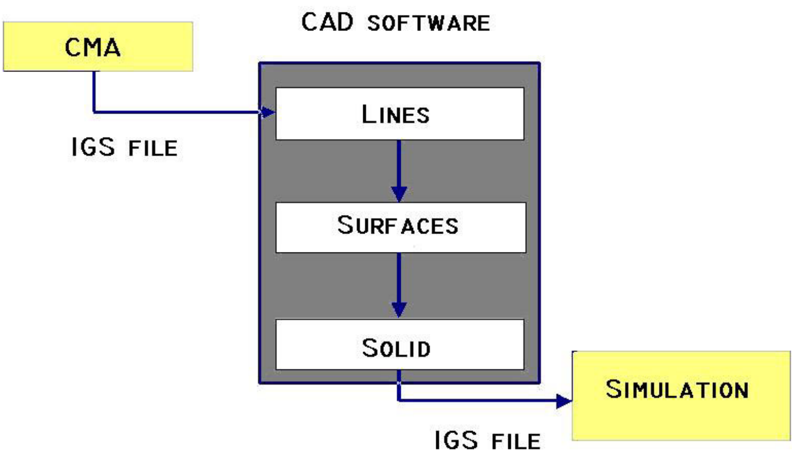

Figure 3 – Data processing routine

The measurement strategy begins by mapping lines in longitudinal and radial orientations on both surfaces of the Kaplan turbine runner (Fig. 4). The measurement was conducted by capturing points in one direction at a time, and establishing the total number of points per line.

Figure 4 – Mapped lines on Kaplan turbine runner surface

The first measurement was carried out in radial direction, capturing 66 points per line in 17 lines per surface (1222 points per surface and a total of 2444 points). It was spent 2.5 hours in measurement. A new measurement was performed applying the same procedure but increasing the number of lines to 18 and reducing the number of captured points per line to 10. This resulted in 180 points measured per surface and a total of 360 points, which took 1.5 hour to be captured.

Another measurement was carried out in longitudinal direction, capturing 30 points per line in 12 lines (360 points per surface and total of 720 points). 2.5 hours were spent in this data acquisition. This same measurement procedure was repeated to measure 10 points per line, resulting in 120 points per surface and a total of 240 points during 1.5 hour.

3. VIRTUAL SURFACES AND SOLID KAPLAN RUNNER

The groups of points determined were adjusted according to splines using G-Pad software, and these lines are shown in Fig. (5). These measurements were taken in radial direction. A general view of the runner profile may be observed in this figure. An IGS format file was exported by G-Pad to generate the runner surfaces at Rhinoceros software. Magnam and Pastorel (2000) pointed out that simply using these splines is not sufficient to develop an acceptable surface. They argue that may be necessary to adjust the lines after measurement to reduce the errors. Nevertheless, we had carefully measured the Kaplan runner and want not to spend much time with adjustments during Computer data processing, unless it is strictly necessary.

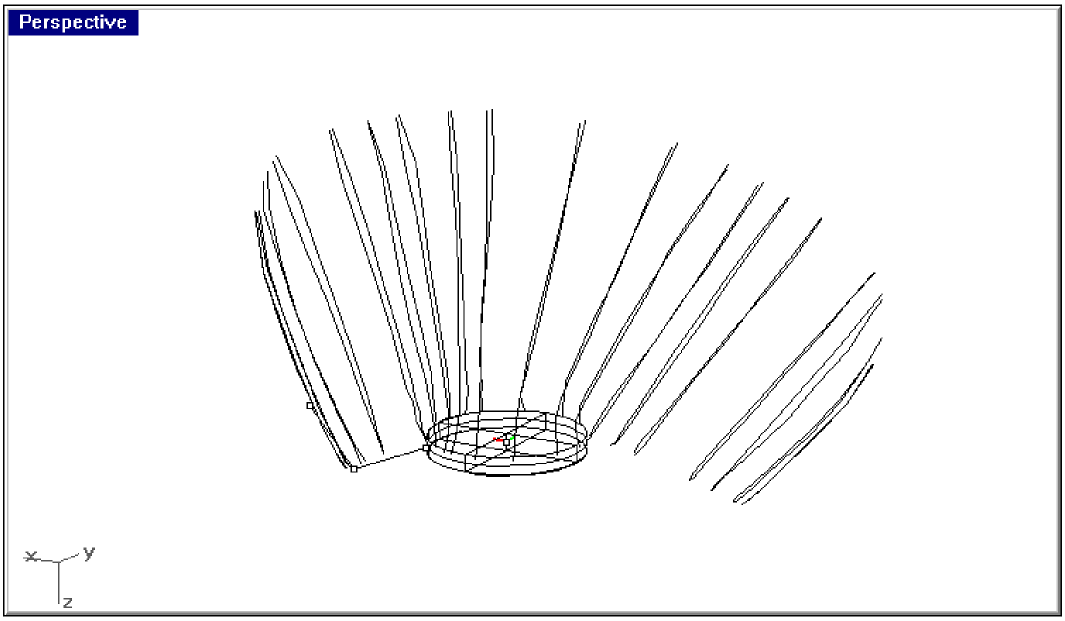

Figure 5 – Splines generated using experimental data points

The surfaces were obtained using Rhinoceros software. A grid pattern was then generated with 15 grid points to produce these surfaces, which are depicted in Fig. (6). A view of the runner surfaces was presented using Rhinoceros render and shade commands. The surfaces showed good profile contours and no adjustment was necessary. Some contours at base border were verified and improved with Rhinoceros.

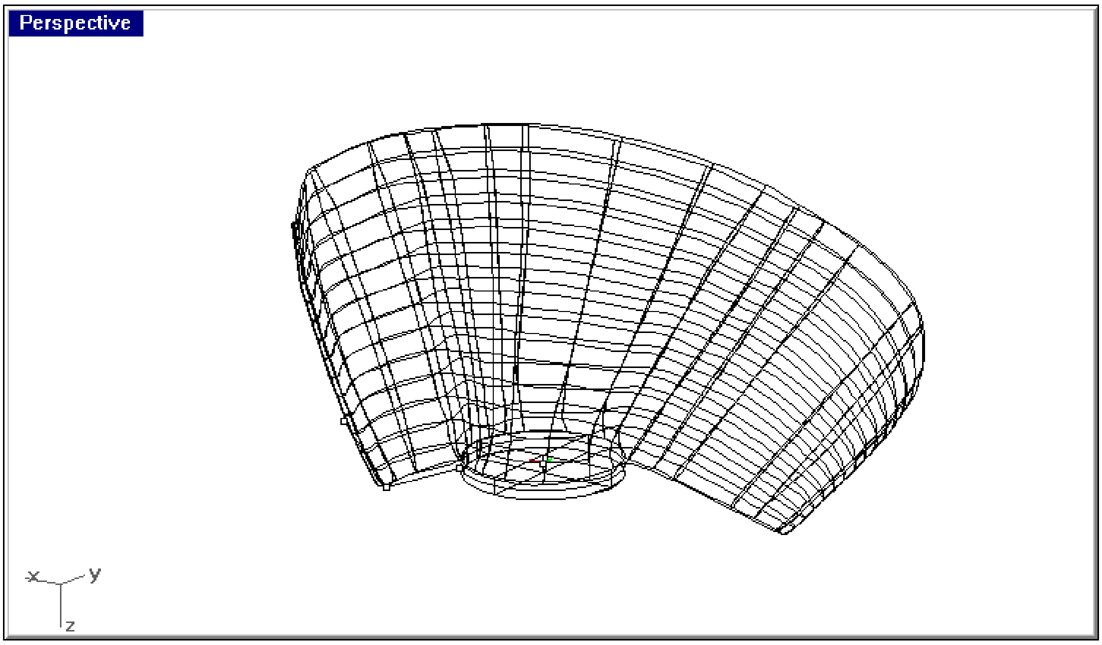

Figure 6 – Grid with 15 points over experimental data

The solid runner was created using SolidWorks software after importing the IGS format files containing the surfaces. Figure (7) shows the resulting Kaplan runner. Visual inspection was carried out along solid borders and it was observed a good agreement between the Kaplan reconstructed model and the prototype. A more precise inspection will be performed using G-Surf software and the determination of quantitative variation between created surfaces and real surfaces (measured) is object of future research.

It was observed that measuring at radial direction produced best results than measuring at longitudinal one. The adjustment of surfaces using radial direction was most suitable as we can adjust splines with same number of points but at smaller length than in longitudinal direction. Reduced number of points produced good surface adjustment and it is preferred as the time spent in measurement is smaller than taking more points.

Magnam and Pastorel (2000) and Dumoulin et al. (1994) developed measurement strategies applied to Francis turbine blades. They pointed out difficulties related to measurement of blades assembled in turbine runners and to the reconstruction of edges during CAD processing. The strategies proposed as similar, differing in aspects like measurement direction in relation to methodology presented in this work.

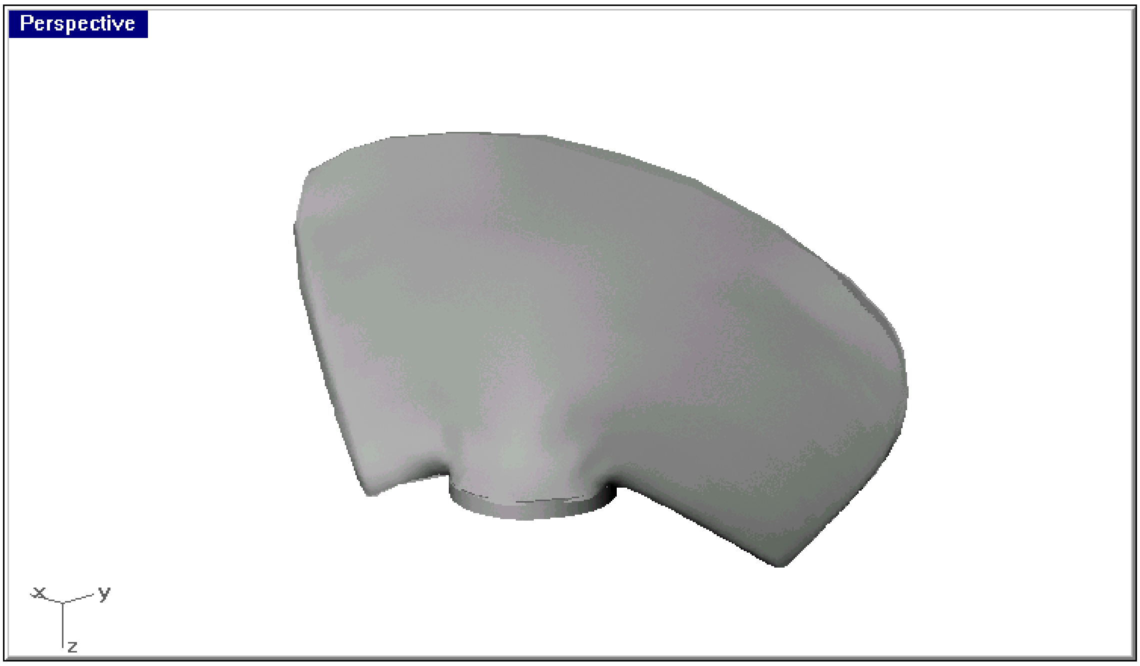

Figure 7 – Kaplan solid runner reconstructed on CAD software

4. CONCLUSION

Techniques of virtual reconstruction were successful applied to generate a Kaplan solid runner. Two measurement strategies were proposed based on radial and longitudinal directions. It was observed that the best results were obtained by the first approach, which involved the determination of 340 points along the radial direction of the turbine runner. The time spent in this measurement was 2 hours.

Efforts of CAD processing were necessary to develop the surfaces and the solid runner on Computer. The most time consuming operation was the adjustment of curves generated on G-Pad software in runner surfaces. The total time spent in this step was about 1 hour.

The solid runner showed good agreement between experimental data and CAD models. Visual inspection on a Computer allowed us to conclude that the number of points determined was sufficient to obtain a suitable adjustment of surfaces. Additional research is planned to investigate the magnitude of errors involved in the surface generation process and in the solid creation.

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6. REFERENCES

Cho, M.W. and Kim, K. New inspection planning strategy for sculptured surfaces using coordinate measuring machine. *International Journal for Production Research*, 33 (2): 427-444, 1995.

Chung, S.C. CAD/CAM integration of on-the-machine measuring and inspection system for free-form surfaces. *Proceedings of ASPE Annual Meeting*, Monterey, CA, USA, 1999.

Dumoulin, Ch. et al. Geometry recovery of a Francis runner prototype at site. *Proceedings of 17th IAHR Symposium*, Beijing, China, 1994.

IEC 60193 Standard, "Hydraulic Turbines, Storage pumps and Pump-Turbines – Model Acceptance Tests". International Electrotechnical Comission, Geneve, nov. 1999.

Ip, W.L.R. and Loftus, M. Adaptive and compensation methods in free-form surface assessment. *Proc. Instn. Mech. Engrs., part B: Journal of Engineering Manufacturing*, 210: 135-45, 1996.

Kovac, I. and Frank, A. Testing and calibration of coordinate measuring arms. *Precision Engineering*, 25: 90-9, 2001.

Magnam, R. and Pastorel, H. Geometry measurements of hydraulic turbine runners. *Proceedings of 20th IAHR Symposium*, Charlotte, NC, USA, August 6-9, 2000.

Piratelli-Filho, A. and Giacomo, B.D. CMM uncertainty analysis with factorial design. *Precision Engineering*, 27: 283-288, 2003.

Thompson, W.B. et al. Feature-based reverse engineering of mechanical parts. *IEEE Transactions on Robotics and Automation*, 15 (1): 1-10, 1999.

Wilhelm RG, Hocken R and Schwenke H. Task specific uncertainty in coordinate measurement. *Annals of the CIRP*, 50/1: 2001.