Obtaining the CAD Flow Models in the Francis Turbine of the Sancancio Hydroelectric Power Plant by Means of Reverse Engineering

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Abstract: This article presents the process for obtaining the CAD flow models in a Francis turbine. The analysis stage in this turbine includes the use of the latest generation optical equipment to obtain the surfaces of each of the component elements of the Francis turbine. After obtaining 3D scans, is used special software for CAD modelling and reverse engineering to extract the complex NURBS surfaces of several main turbine components, finally the flow volumes which are of vital importance in the previous studies of the research called CFD computational analysis of the influence on the opening of the blades in a Francis turbine on the side of the suction ring in the small hydroelectric power station of Sancancio belonging to the CHEC S.A E.S. P EPM Group

Keywords: Francis Turbine, Model CAD (Computer-aided-design), Reverse engineering, Surface NURBS, CFD (Computacional Fluid Dynamics)

1. Introduction

Hydropower was one of the first forms used to produce electricity and it is now the second and most widespread source of electricity in the world, as shown in Figure 1. The world's installed hydropower capacity at the end of 2017 was 1,267 GW and is expected to reach 3606 TW by 2020[1]. Colombia is a country with a great water resource with great potential for the application of hydroelectric power plant; currently it has a large number of them which provide 68% of the installed capacity of electricity generation in the country as shown in figure 2 [2]. Figure 3 shows Colombia's energy production at the end of 2018 the installed generation capacity in the national interconnected system was 17,313 MW [3]. Within the field of turbomachines there are so-called hydraulic turbines, which are machines that transform the potential and kinetic energy of a water current through an impeller, which has a characteristic design in the geometry of its blades that allows the fluid to deliver part of its kinetic energy to the rotor generating a thrust to it and to generate torsion to the shaft that is coupled to the electric generator. Figure 4 specifies the different types of existing water turbines [4].

Among the different types of hydraulic turbines, most commonly used both internationally and nationally, are the Francis type, because they can be designed for a wide range of head and flows and are capable of operating on slopes ranging from two meters to several hundred meters. This, together with its high efficiency, has made this type of turbine the most used in the world. This type of turbines is also known as overpressure turbines, total intake turbines or reaction

turbines, the field of application is very wide and can be used in different heights, in a wide range of flows between 2 and 200 m³/s approximately [4]. In general, this type of fluid machine has taken special interest worldwide due to its generation capacity, which is linked to the conditions of flow rate and net head of the plant. For this reason, these conditions will define the type of turbine to be used and the specific design of its components, which are unique to each plant [5]. The main components of a Francis turbine are shown in Figure 5.
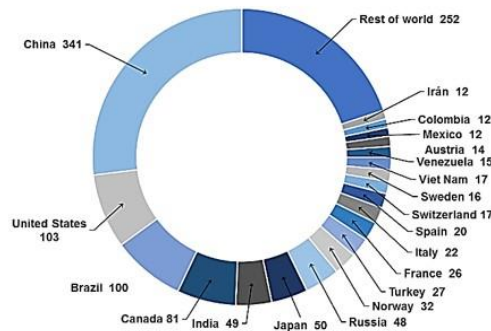

Fig. 1 - Hydropower installed capacity (GW) of top 20 countries including pumped storage in 2017. Source: IHA 2018 [1]
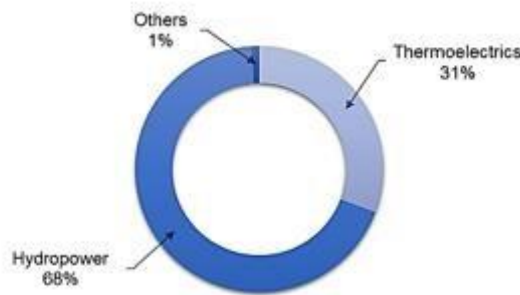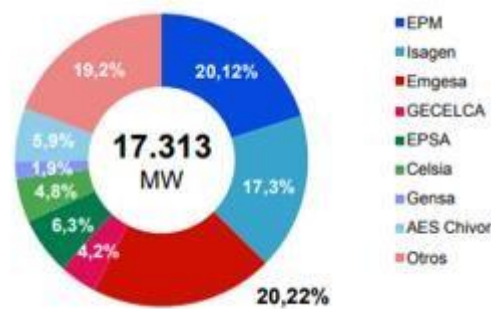

Fig. 2 - Energy production in Colombia [2]

Fig. 3 - Installed capacity of electricity generation in the country by Energy Companies [3]
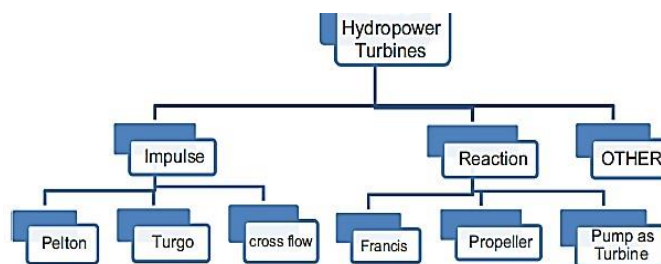

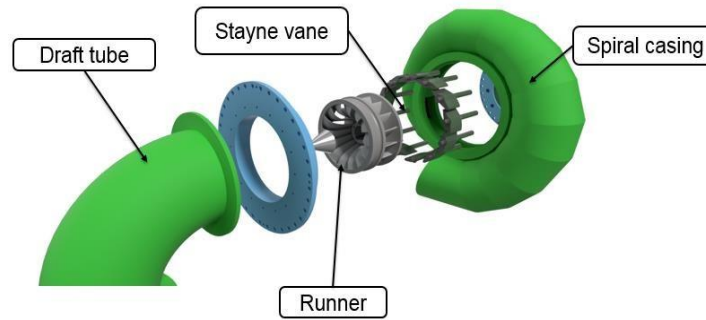**Fig. 4 - Classification of hydraulic turbines [4]**

Fig. 5 - Main components of the Francis turbine at the Sancancio hydroelectric power plant

Due to the great complexity of the turbine geometry, especially the impeller, CHEC S.A. E.S.P part of the EPM group, only has 2D drawings of the Francis unit, whose characteristic data are specified in Table 1.

Table 1 - Technical data sheet Francis hydroelectric central turbine of Sancancio

Technical data sheet	
Turbine type	Francis
Unit	1
Manufacturer	LEFFEL
Number of serie	W 2453
Fabrication year	1947
Velocity (RPM)	600
Head (m)	53,9
Flow (m³/s)	2.5
Power (MW)	1.2

Therefore, in the first phase of this investigation, the three-dimensional models of each of the turbine components should be obtained in order to generate the flow volumes required for the preceding CFD analyses. The use of reverse engineering focused on the three-dimensional reconstruction of surfaces for parts or products that already exist in the real world, but which are not available in digital media or only have 2D drawings, has gained considerable strength in recent years, due to the reduction in the cost of scanning equipment, the increase in the computing capacity of current computers and the refinement achieved by commercial reverse engineering programs are already at a level suitable for large scale work such as that presented in this study [6].

However, in the literature reviewed, the number of reverse engineering studies focused on Francis turbines is small, for example Larrahondo and Teran [7], they present a Computational Fluid Dynamics (CFD) analysis study to obtain a new impeller geometry that provides greater efficiency in a 500 kW Francis turbine. This analysis was developed in two parts: The first stage of the work focused on obtaining the CAD models of the turbine by means of a three-dimensional scanning process and a reverse engineering process in order to obtain the flow models that were subsequently used in the optimization process by means of CFD computational simulation that predicted a 14.77% increase in turbine efficiency.

Bogdan, D Nedelcu [8] present an engineering study of a Francis slide geometry with a diameter of 1160 mm and 19 blades, which, after 50 years of operation, has pronounced wear marks, high porosity surfaces and areas of cracking. The geometry is scanned using the photogrammetry technique and processed with the following software packages: Agisoft Photoscan, Geomagic Design X and finally, the solid geometry and the impeller drawing were generated with SolidWorks software.

Franco and Tamariz [9] performed an optimization study on a Francis impeller by a process implemented in a commercial CFD code that combines genetic algorithms and a trained artificial neural network (ANN). CAD models were obtained by means of a three-dimensional laser triangulation by means of a portable coordinate measurement system based on the optical digitizing system (scanner technology).

Rodriguez and Garcia [10] present the process followed for the three-dimensional reconstruction of the impeller of a medium-sized Francis turbine, which presents a great difficulty for scanning, given the complexity of the inner channel in the blade, which is difficult to access for any available scanning device. The process followed from scanning the part

using a laser scanner, the strategy used to access the internal surface of the blade, and the general reconstruction process of the surfaces using commercial reverse engineering software, as well as the final applications of the reconstructed three-dimensional model are shown here.

There is also research on CFD simulation or reconstruction of small Francis type impellers in which the process of obtaining the CAD models of the turbine by means of a three-dimensional scanner and inverse engineering is shown [11, 12]. There are also studies of Kaplan type hydraulic turbines such as the one presented by D Nedelcu, S L Bogdan and Pădurean [13]. In which it is illustrated the reverse engineering process of a blade, from a Kaplan runner with a diameter of 5400 mm, using the following software packages: Agisoft Photoscan and Geomagic Design X (formerly Rapidform XOR); the next step was to generate the solid geometry of the blade using the SolidWorks software. The last step was to compare, using GOM Inspect software, the geometry of the designed blade with the corresponding geometry obtained using Photogrammetry and finally answer the question if this technique can be used in the mechanical field to get a precise 3D reconstruction of large objects with complex geometries.
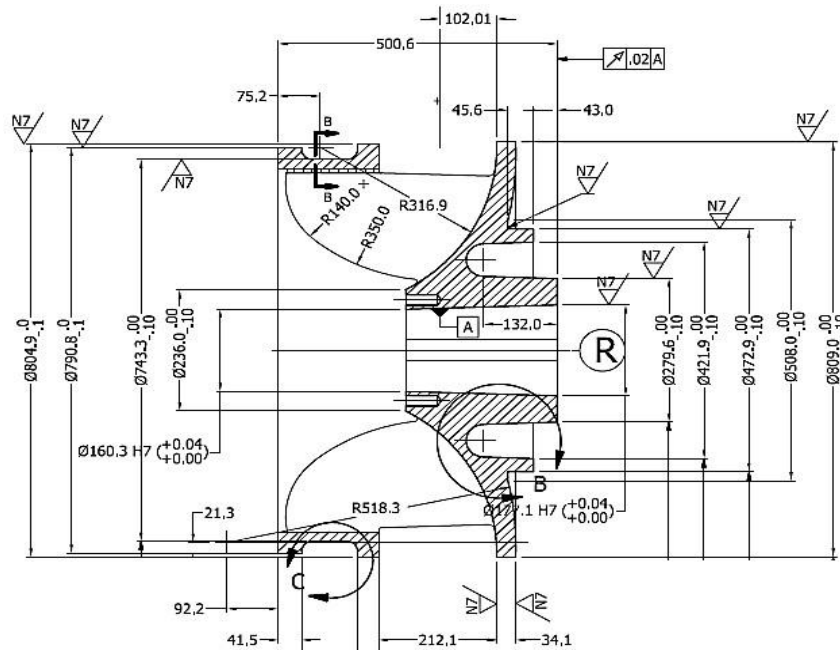

Fig. 6 -Two-dimensional drawing of the Francis de Sancancio turbine runner, courtesy of CHEC S.A E.S.P

Srdjan Zivkovic and Luka Cerce [14]. The study presents the reverse engineering procedure for the reconstruction of the turbine blades for small hydropower plants. The blade in best condition was scanned using an optical scanner. Starting from the STL model, the surface of the blade was redesigned, so that all damages and deformations were corrected. However, it is important to emphasize that the potential of reverse engineering lies in the need for the development of new products in an increasingly technological, competitive and globalized industrial world, in which the diversity of products, together with ever shorter life cycles and the progressive increase in quality requirements, make it necessary to optimize the time and costs associated with the processes of research, development and innovation in production companies. It is therefore common today to find reverse engineering studies focused on product development and optimization of mechanical components other than hydraulic turbines among which the following stand out.

Mohaghegh and Bdullah [15].The study shows that a small change in blade geometry can lead to a large change in turbine performance. The authors believe that the only way to capture the valid shape of a blade profile outside of the many manufacturing deviations is to incorporate key design points during reverse engineering. Gopinath Chintalaa and Prasad Gudimetl [16].They present a study of the modeling and analysis of gas turbine blades. The design data of a turbine blade is obtained using the reverse engineering technique. From the data thus obtained, a model of the turbine blade is created in the ANSYS FEA package. For the given load conditions, the blade is analyzed for static structural analysis of different materials with variable centrifugal loads and different materials, and a safe and feasible material is suggested.

Finally, Jinsheng Kang and Zhuang Xiao Qiu [17]. They present a study describes a complete set of unique and novel techniques which constitute the principles and methodology for large scale wind turbine blade reverse engineering and redesign. The research based on reverse engineering CAD technique to redesign the large-scale wind turbine blade, has incorporated the measurement of a large set of blades and use of reverse CAD modeling, the postprocessing of data, precision analysis and the resize to original state.

Therefore, the objective of this article is to establish a working methodology for obtaining CAD models of a Francis turbine from a reverse engineering process, these models will later be used for the generation of fluid volumes in the turbine and later will be used in CFD analysis. It should also be mentioned that due to the non-existence of 3D CAD models of the turbine due to the fact that it was manufactured in 1940, only 2D drawings of some of the main components

of the machine are available as shown in figure 6, therefore it is essential to use a 3D scanner in order to focus the complex surfaces of some of the main components in the turbine such as the runner and spiral camera.

Therefore, in this case, a commercial   brand laser scanner was used. Due to the fact that the detailed characteristics of the components of the turbine are to be obtained without the help of any original plan of these elements, in addition to the high degree of complexity of the surfaces of the runner it is necessary to apply this type of technology The reconstruction process has been performed in commercial software Inventor Professional until, a digital 3D model is obtained, and it will later be used for further engineering analysis.

2. Methodology

The methodology for obtaining the CAD models of the turbine is shown in figure 7. This methodology has been used for the processing and subsequent modeling of each of the components of the Francis turbine [18].
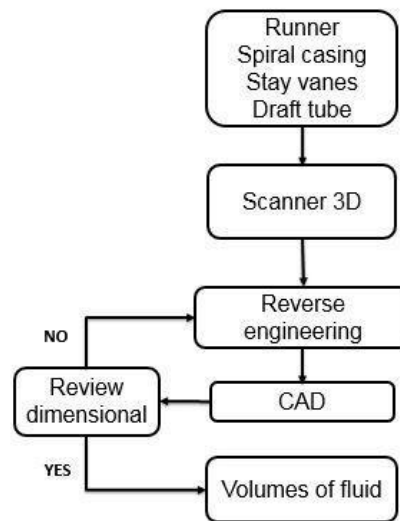

Fig. 7 - General methodology for obtaining CAD models of the Francis turbine

In this first stage of the investigation, an ATOS Core 3D industrial optical measurement equipment was used, which is shown in figure 8 and has calibration certificates according to the VDI/VDE 2634 standard for the equipment and PTB and NIST certificates for the GOM Inspect software for free use in the basic version, which has been used for the reconstruction of surfaces not focused by the scanner. The reverse engineering process consists of three general steps as shown in Figure 9.

2.1 Data capture

It is the acquisition of the scanning areas by ranges is characterized by having a polygonal mesh format, a laser scanner will be used which is a scanning tool that emits a laser point on an object and through a camera identifies the position of the point on it as shown in Figure 10. This technique is also known as triangulation, because the emitted laser and the camera form a triangle inside it to identify how far away the piece is. This technique results in a 3D digital image of the object, formed by triangles. The advantage of using a laser scanner for the digital reconstruction of an object is that a good three-dimensional representation of the object is obtained, with an accuracy of up to 0.02mm [19].

Therefore, a previous preparation of each of the parts of the turbine components to be scanned is required, reflective points should be positioned on each turbine component, according to the recommendations of the scanner manufacturer as shown in figure 11, three of these points should form triangles and will be installed on the entire geometry of the turbine, since the points indicate the orientation of the object while scanning. The effectiveness of the scanner also depends on the surface finish of the object, because the brightness of the object can have a negative influence on the scanning phase [10], which makes it necessary to use substances such as matt or dull paint and powder as spray talcum as shown in figure 11.Therefore, the scanner has been positioned to facilitate the capture process of the complex surfaces that make up the impeller, which is the most complex element to process due to its geometry. Figure 12 shows the scanning process of the impeller input channel. After this process the pressure and suction faces are scanned as shown in Figures 13 and 14. It is important to mention that the same procedure has been developed for the auxiliary elements of the turbine such as spiral casing, guide vanes, fixed vanes and draft tube.
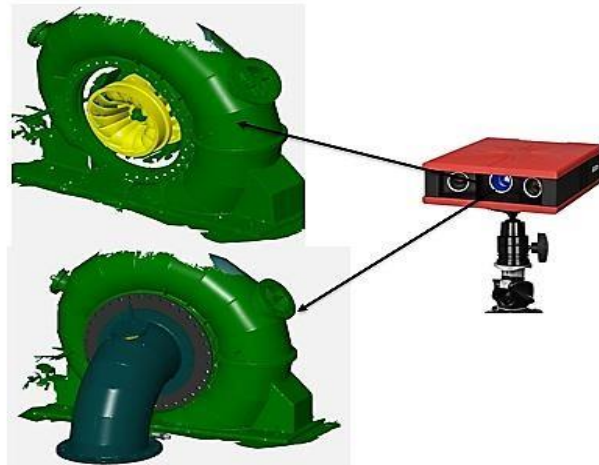
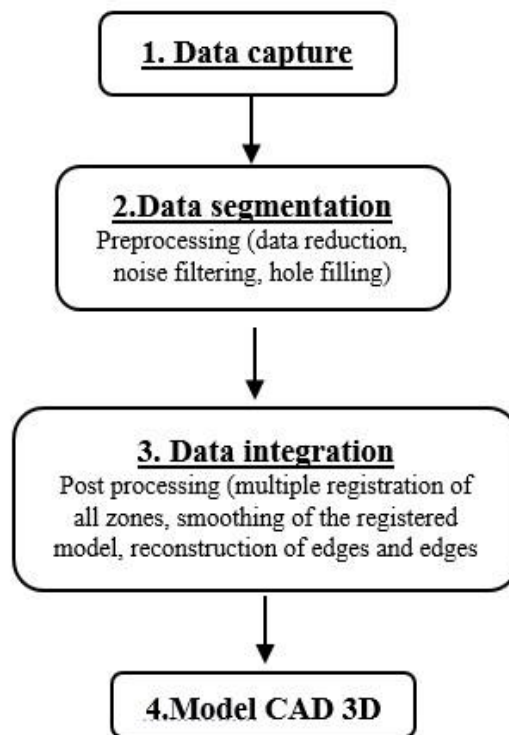**Fig. 8 - Gom Inspect scanner used in the Sancancio hydroelectric power plant**

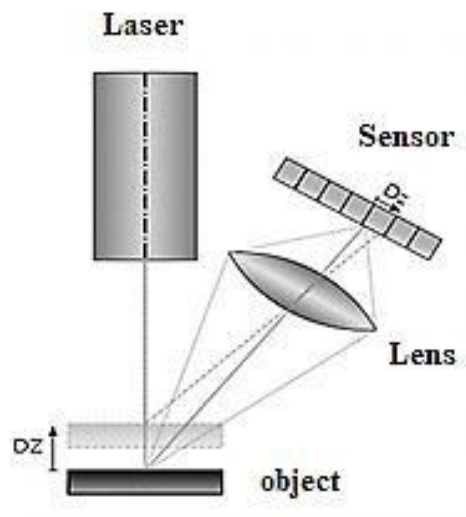**Fig. 9 - General reverse engineering procedure [18]**

Fig. 10 - Scanner laser principle of operation

Fig. 11 - Location of reflective points and application of white powder in Francis central hydroelectric impeller of Sancancio
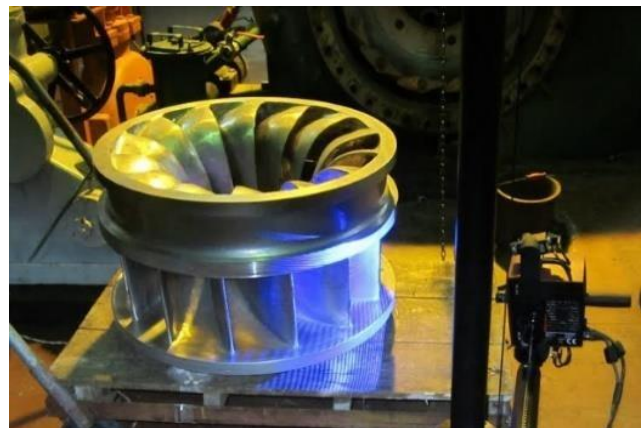

Fig. 12 - Scanning process of the input channel into the Francis runner
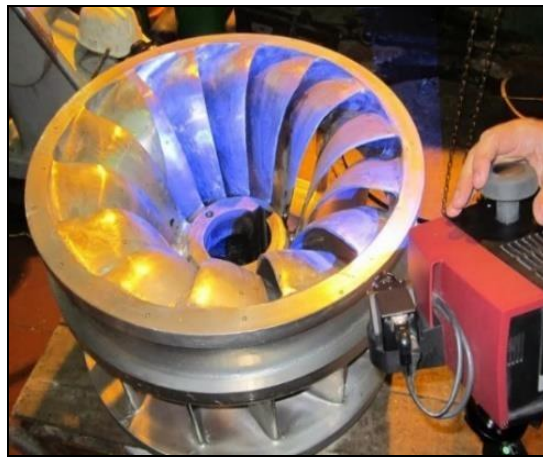
Fig. 13 -   Scan face pressure Francis runner

Fig. 14 - Scan face suction Francis runner 3. Data Segmentation

In this processing stage, data reduction and hole filling operations were carried out on the polygonal meshes, this process being carried out with the software Gom Inspect free version. This allows the corrections to be made to previously scanned models as shown in Figure 15.
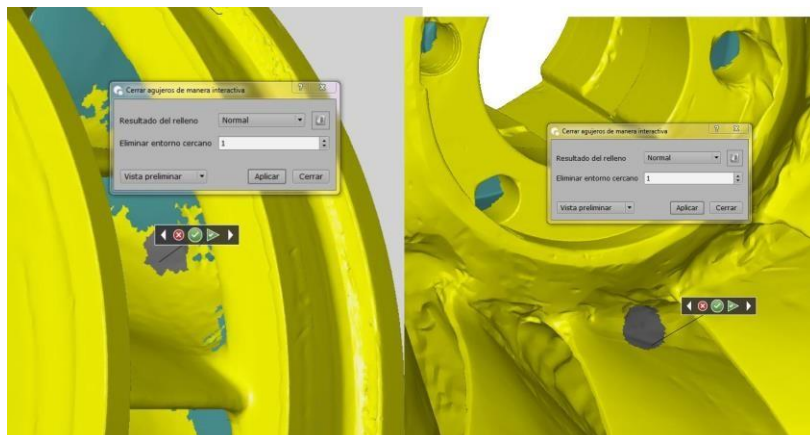

Fig. 15 - Polygon mesh correction of the Francis runner 4. Data Integration

It is the post-processing stage in which a multiple recording of all the zones of the scanned components has been performed, and consequently a smoothing of the registered models as shown in figure 16, followed by a reconstruction of edges and edges by means of the software GOM Inspect in free version. Once the point cloud has been refined, the software Gom Inspect will be used again to obtain the characteristic curves of the blades in the current impeller as shown in figure 17, and to export them to a CAD modeling software to obtain the characteristics of the complex surfaces of the Francis runner blades [20]. The same process will be carried out with the other turbine components such as guide vanes, fixed vanes, spiral casing and draft tube.
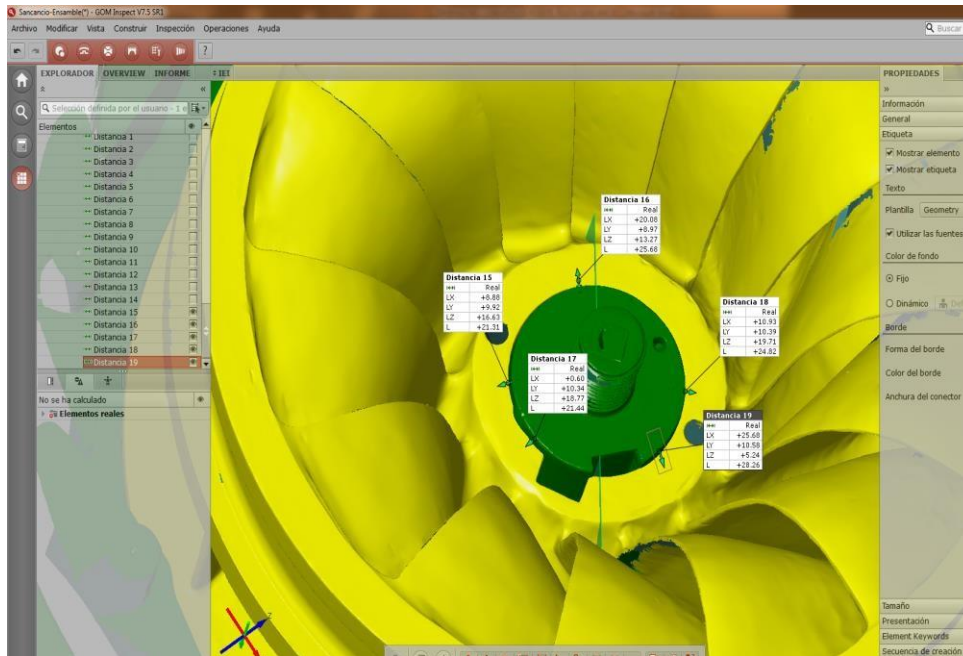
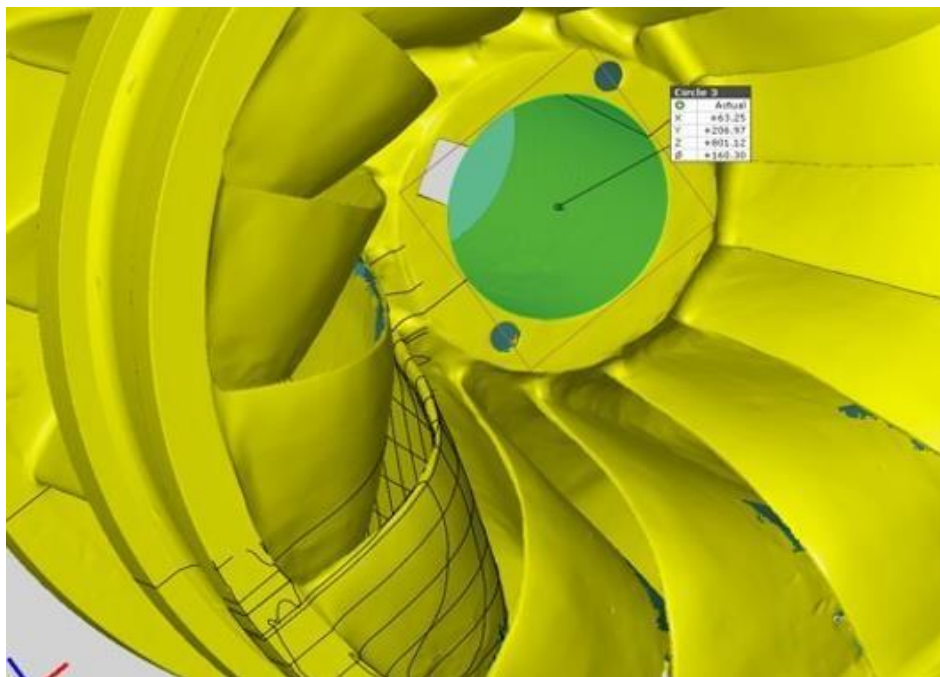**Fig. 16 - Smoothing of registered models software Gom Inspect version free**

Fig. 17 - Obtaining characteristic curves of the Francis runner

5. Results obtained

Figure 18 shows all the scanned components of the turbine therefore, a dimensional comparison has been made between the point cloud obtained in the scanner and the CAD models made in the Autodesk Inventor Professional software. Each of the dimensional parameters by the scanning proceess is then specified. The CAD models have been obtained based on the polygonal meshes using the commercial software Gom® Inspect Free version.

Fig. 18 - Point cloud Francis turbine complete Sancancio hydroelectric power plant 6. Runner

The runner is the main component of the turbine where the energy exchange between the machine and the fluid takes place. Figure 19 shows the surfaces obtained in the CAD model and the scanner. The characteristic dimensions at the impeller are specified in figure 20. In order to verify the results of the scanning process, a comparison between CAD model and scanner surface were performed on the Francis runner as shown in figure 21. Four differents points at each blade section were used in order to compare the gap between scanner and CAD surface model. Table 2 summarize the all results and the average of the separation, denoted by Dp for each blade section.
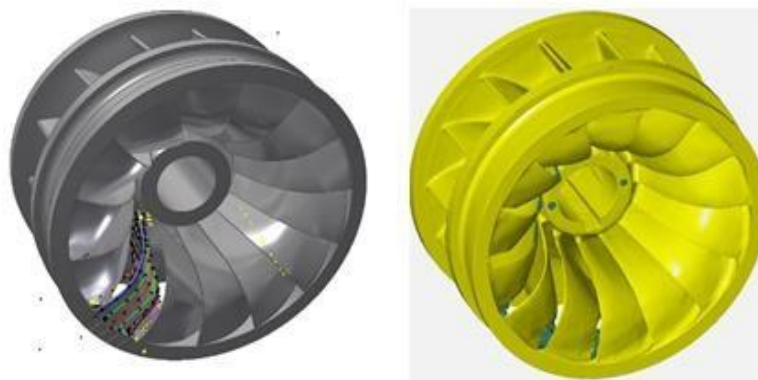

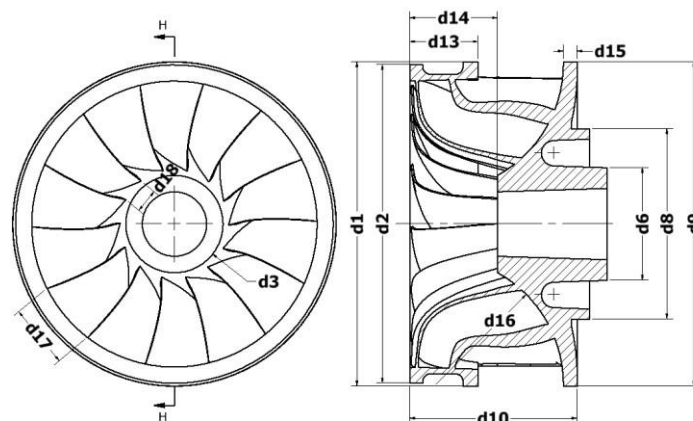**Fig. 19 - CAD model and runner scanner**

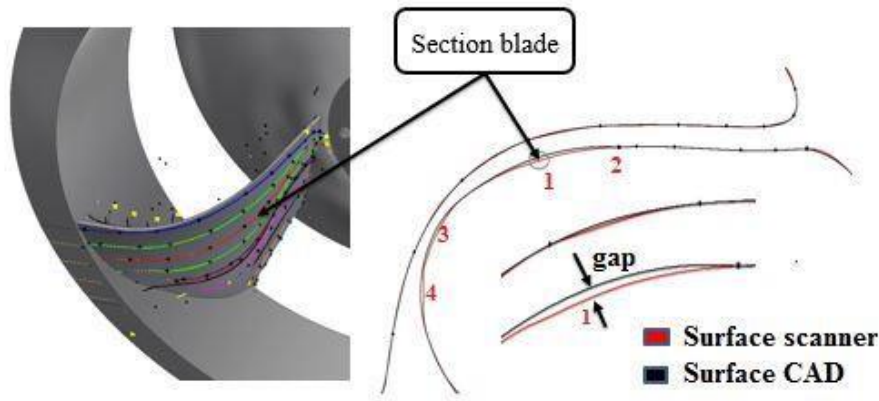**Fig. 20 - Dimensional parameters evaluated on the runner**

Fig. 21 - Comparison of surface dimensions obtained from the scanner and the CAD model

Table 2 - Dimensional variation in blade profiles between scanner surface and CAD model

Blade Section	Gap [mm]				Dp [mm]
	1	2	3	4	
1	0.65	1.86	1.42	0.85	1.20
2	0.35	0.45	0.68	0.20	0.42
3	1.86	1.56	1.75	0.90	1.52
4	0.46	1.02	0.82	0.23	0.63
5	0.55	1.60	1.48	1.00	1.16
6	0.98	1.17	1.25	1.56	1.24
7	0.23	0.25	0.35	0.24	0.27
8	0.27	0.35	0.35	0.28	0.31
9	0.26	0.45	0.27	0.10	0.27
10	0.65	0.78	0.62	0.45	0.63
11	0.33	0.35	0.27	0.40	0.34
12	0.26	0.65	0.56	0.32	0.45

7. Spiral casing

Its function is to distribute the fluid evenly at the impeller inlet. The spiral or snail shape is due to the fact that the average speed of the fluid must remain constant on its perimeter. In figure 22 the 3D scanner and the CAD model are shown. For each section of the spiral casing, a comparison between scanner and CAD model were performed using the diameter-d of the section. The results are shown in table 3. The characteristic dimensions obtained in the spiral casing are specified in figure 23.
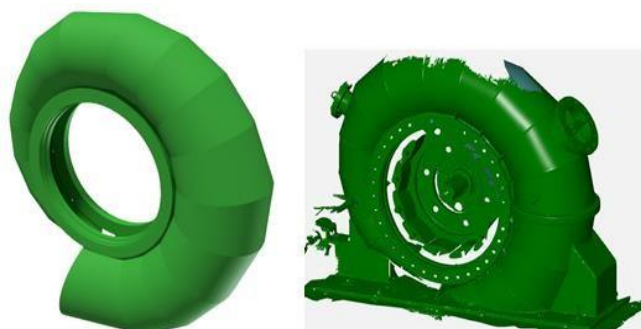

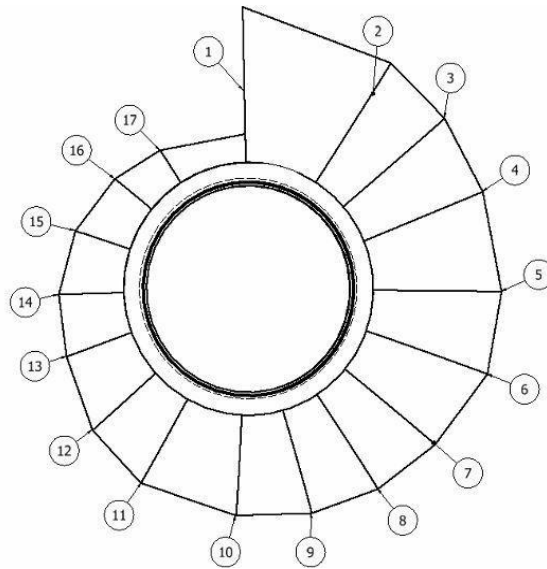**Fig. 22 - CAD model and spiral casing scanner**

Fig. 23 - Dimensional parameters evaluated in the spiral casing

Table 3 - Dimensional variation in spiral casing between scanner surface and CAD model

Section	Scanner [mm]	CAD [mm]	Difference [mm]
d1	901.42	901.40	0.02
d2	824.12	824.45	0.33
d3	790.85	790.98	0.13
d4	761.89	761.77	0.10
d5	761.82	761.77	0.05
d6	761.83	761.77	0.06
d7	695.23	695.63	0.40
d8	661.97	662.78	0.81
d9	628.32	628.59	0.27
d10	592.23	592.17	0.06
d11	568.45	568.33	0.12
d12	507.74	507.70	0.04
d13	421.89	421.57	0.32
d14	398.92	398.67	0.25
d15	356.78	356.31	0.47
d16	295.32	295.60	0.28

8.0 Draft tube

The draft tube is the component that allows the continuity of the flow in the discharge and recovers the lost jump in the installations that are above the water level at the outlet. In figure 24 the 3D scanner and the CAD model are shown. The characteristic dimensions obtained in the suction elbow are specified in figure 25. The results obtained in the parameters verified in the draft tube are shown in table 4.
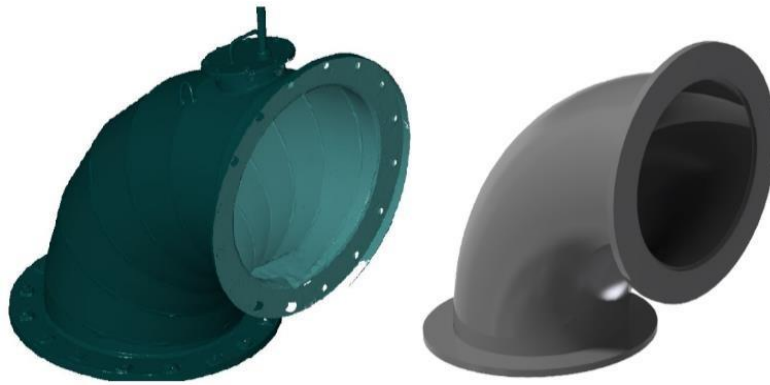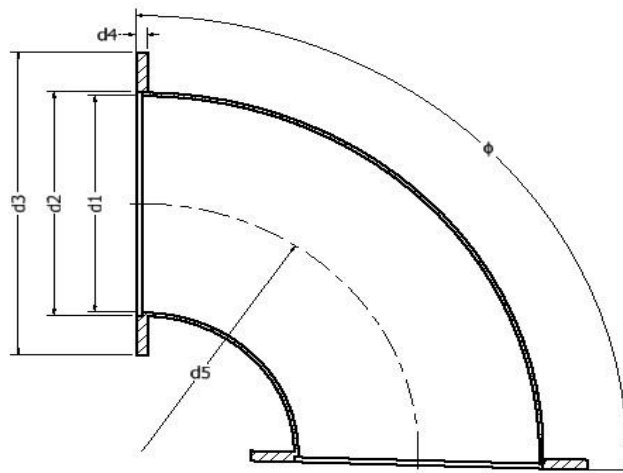
Fig. 24 - Model CAD and scanner draft tube

Fig. 25 - Dimensional parameters evaluated at the draft tube

Table 4 - Dimensional variation in suction bend between scanner surface and model CAD

Dimension	Scanner	CAD [mm]	Difference
d1	1050.32	1050.0	0.32
d2	776.23	776.0	0.23
d3	751.56	751.0	0.56
d4	35.0	35.0	0
d5	863.38	863.0	0.38

9.0 Guide vanes

The guide vanes are located in the distributor and are designed to direct the water towards the runner blades, controlling the flow rate. Figure 26 shows the surfaces obtained in the CAD model and the scanner. The characteristic dimensions obtained from the guide vanes are specified in figure 27. The results obtained in the parameters verified in the draft tube are shown in table 5. Finally, the flow volumes were obtained by means of CAD modeling, which are required in the CFD analysis [21], [22]. Figure 27 and 28 shows the flow components considered in this study.
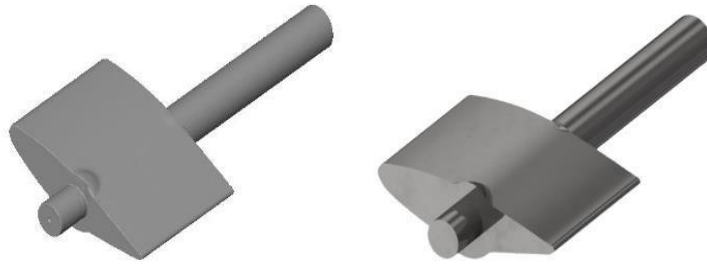
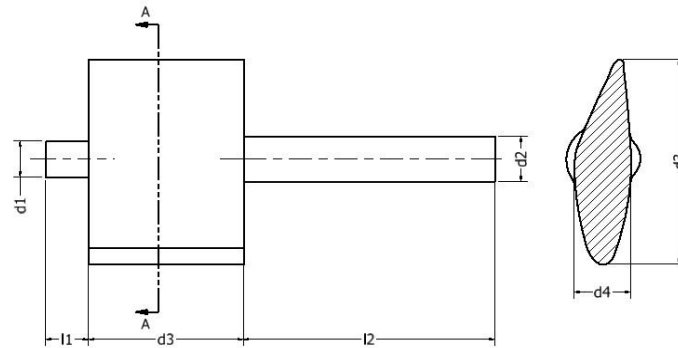**Fig. 26 - Dimensional parameters evaluated at the draft tube**

Fig. 27 - Dimensional parameters evaluated in the guide vanes

Table 5 - Dimensional variation in guide vanes, between scanner surface and model CAD

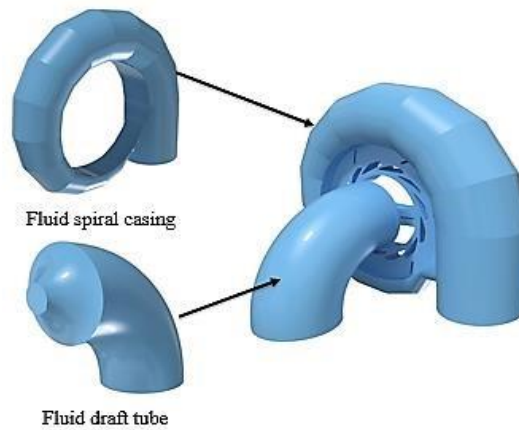| Dimension	Scanner	CAD	Difference
		[mm]	
d1	50.03	50.03	0
d2	62.98	63.01	0.03
d3	286.45	286.47	0.02
d4	77.01	77.01	0
l1	58.53	58.50	0.03
l2	342	342.15	0.15

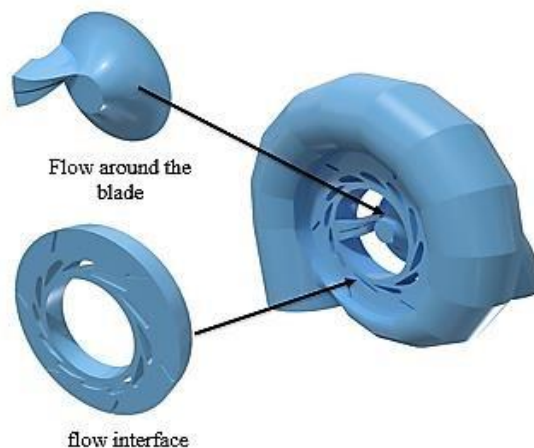**Fig. 28 - Flow spiral casing and flow in draft tube**

Fig. 29 - Flow around the blade and flow interface in the turbine Francis

10.0 Conclusions

In this phase of the investigation, the volumes of fluid components of the turbine were obtained, which are important for the CFD simulation process. The surface of the main elements of the Francis turbine was digitized by 3D optical metrology equipment with an accuracy of +/- 0.02 mm in the areas focused by the scanner, the differences obtained between the surfaces of the CAD model and the scanner were minimal for the different components of the turbine and do not represent a critical variation of the geometry for the next step of the engineering CFD simulation. The simulation process will then focus on the discretization phase and specification of boundary conditions in order to configure the CFD simulation. With the reverse engineering software, it was possible to register and join the different scanning zones, in addition the tools for the reconstruction of the edges of the part allowed for a very adequate reconstruction. The surfaces obtained also allow them to be exported easily and with great compatibility to other applications where required.

Acknowledgement

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