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Reverse Engineering of Turbine Blades Kaplan's type for Small Hydroelectric Power Station

Srdjan Zivkovic[a,*], Luka Cerce[b], Julija Kostic[c], Vidosav Majstorovic[c], Davorin Kramar[b]

[a]Military Technical Institute, Ratka Resanovica 1, Belgrade 11030, Serbia
[b]University of Ljubljana, Faculty of Mechanical Engineering, Askerceva 6, Ljubljana 1000, Slovenia
[c]University of Belgrade, Mechanical Engineering Faculty, Kraljice Marije 16, Belgrade 11120, Serbia

* Corresponding author. Tel.: +381-66-8721403; fax: +381 11 250-8474. E-mail address: srdjan.vti@gmail.com

Abstract

The paper presents the reverse engineering procedure for the reconstruction of the turbine blades for small hydropower plants. The scaled turbine model of Iron Gate I Hydroelectric Power Station on the Danube river has been used for decades under the same exploitation conditions as a large turbine, to simulate the condition of large blades based on the similarity of physical phenomena. The blades of the scaled model have been selected for the small hydroelectric power plant project. Since the scaled turbine model was manufactured in the early 70's, the CAD model is not available. 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.

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Keywords: Reverse Engineeering; Turbine Blades; Small Hydroelectric Power Station

1. Introduction

Nowadays, reverse engineering (RE) is recognized as an important issue in the product design process which highlights inverse methods, deduction and discovery in design. In mechanical engineering, reverse engineering has evolved from capturing technical product data, and initiating manual redesign procedure while enabling efficient concurrency benchmarking to a more elaborated process based on advanced computational models and modern digitizing technologies [1].

Today application of reverse engineering is to producing of 3D digital models of various mechanical worn or broken parts. The main steps in reverse engineering procedure are: sensing the geometry of the existing piece; creating a 3D model; manufacturing by using an appropriate CAD/CAM system [2, 3, 4]. In literature, results concerning the procedure of reverse engineering for the case of turbine blade are available, and we can divide following approaches:

- Simulation / reconstruction of small turbine runners [1].
- Enhancing the accuracy of scanned surfaces [5].
- The static structural analysis materials at various centrifugal loads of blade [3].
- Validation of the new blade design, by similarity between original and reconstructed parts – our approach, more detailed in section 3 and 4.

Nomenclature

X,Y	Coordinate of blade's control points in 3D space [mm]
X_T,Y_T	Aerofoil coordinate in definition plane [mm]
Z_P	Third coordinate on the pressure side in 3D [mm]
Z_S	Third coordinate on the suction side in 3D [mm]
R	Radius of cylindrical section [mm]
U	Aerofoil attack angle in the definition plane [deg]
H_P	Blade position on the hub; Pressure/Suction side [mm]

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1.1. History of the hydroelectric power plant Djerdap

The Iron Gate I Hydroelectric Power Station (Romanian: Portile de Fier I, Serbian: Djerdap I) is the largest dam on the Danube river and one of the largest hydro power plants in Europe. It is located on the Iron Gate gorge, between Romania and Serbia. The project started in 1964 as a joint-venture between the governments of Romania and Yugoslavia for the construction of a major dam on the Danube River which would serve both countries. At the time of completion in 1972, it was one of the largest hydroelectric power stations in the world with twelve units generating 2,052 MW, divided equally between the two countries at 1,026 MW each [6].

Turbine manufacturer: LMZ (Leningradsky Metallichesky Zavod, is the largest Russian manufacturer of power machines and turbines for electric power stations); Turbine Type: Kaplan; Installed power: 194MW; Rpm: 71,5 Max/Min water fall: 30/17,5m.

1.2. Small Hydroelectric Power Plants

In the Serbia and Slovenia also in the world, there are a number of small and medium-sized streams that small hydro power plants can provide inexpensive and always available electricity. The choice of the turbine type depends on the difference in elevation between the headwater surface above and the tail water surface below, and also depends of the average water flow.

The small hydro power plants are often the only source of power in rural areas, isolated commercial facilities such as a timber plants and agricultural products plants, tourist facilities, communication centers and military facilities.

Advantages of small hydro power plants [7]: using small and medium-sized streams, reliable supply of electricity, rational power generation, renewable energy, reliable operation with minimal maintenance.

1.3. Kaplan Turbine

The Kaplan turbine is a propeller-type water turbine which has adjustable blades. It was developed in 1913 by Austrian professor Viktor Kaplan, who combined automatically adjusted propeller blades with automatically adjusted wicket gates to achieve efficiency over a wide range of flow and water level. As shown in the analysis [7], Kaplan turbine is suitable for flow rate from 0,5 to 50 m^3/s and Head from 3 to 55m. Pros [8]:

- Kaplan Turbines can achieve efficiency of up to 95%.
- Can be implemented in low-head situations allowing for power plants at lower elevation.
- Varying size of turbine and output allows for micro-hydropower plants instead of large dams.
- Kaplan Turbines are relatively low cost due to the small size and low head requirements.
- Dams build with the Kaplan Turbine design produces less environmental impact because of low head requirements therefore the reservoir area would not be flooded as much as high head dams.

Cons [8]:

- Often times, Kaplan Turbines are installed where fish migrations occur, and may potentially affect their migration patterns and survival rates.
- The high velocity of the turbine may cause leakage of oil-based lubricant into the outlet leading to pollution.
- Due to the high discharge of the turbine, the water around the turbine can reach very low pressure making the Kaplan turbine vulnerable to cavitation.

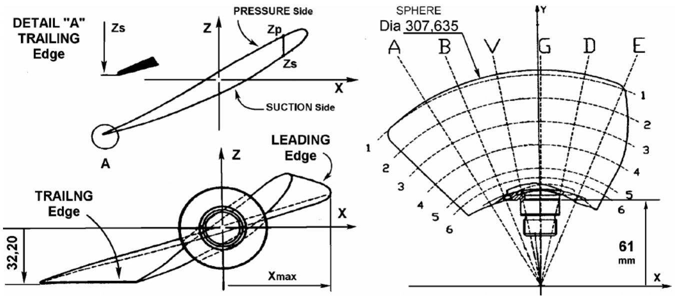
These advantages of Kaplan turbine are the primary reason for choosing this type for small hydroelectric project. Due to positive experiences in exploitation, the scaled model of the turbine of the hydroelectric power plant Djerdap was selected.

2. Scaled Physical Model of Turbine blades

The scaled Turbine model, during decades of exploitation, used to monitor the condition of large blades based on the similarity of physical phenomena. The scaled turbine model has been for decades under the same exploitation conditions as a large turbine. The blades of this scaled model have been selected for the small hydroelectric power plant project.

The scaled turbine model was manufactured in the early 70's (Listostroj factory, Slovenia) and, as expected, there is no computer model of these blades. There were 6 blades and one drawing with incomplete data for control of geometry, Fig. 1.

The drawing clearly indicates that the blade geometry control was performed in 6 cylindrical sections, indicated 1-2-3-4-5-6 on the Fig. 1 which were intersected with 6 directions indicated A-B-V-G-D-E on the Fig. 1, originated from the center of the sphere. The positions of the control points X, Y are clearly defined, but the third coordinate on the pressure side



Z_P and the coordinates on the suction side Z_S is not defined by this control drawing.

Fig. 1. Turbine Blade Model: Coordinate System Orientation

The drawing clearly defines the position of the coordinate system: the trailing edge is on the line at a distance of 32,20mm from the center, the diameter of the boundary sphere is 307,635mm, the center of the sphere is 61mm from the plane of the blade support, Fig.1.

This old drawing as well as 6 blades manufactured in the 70^s of the last century are sufficient starting point for the design of a turbine for a small hydro power plant, using a RE (Reverse Engineering) technique [9, 19].

2.1. Scanned Model of Turbine blade

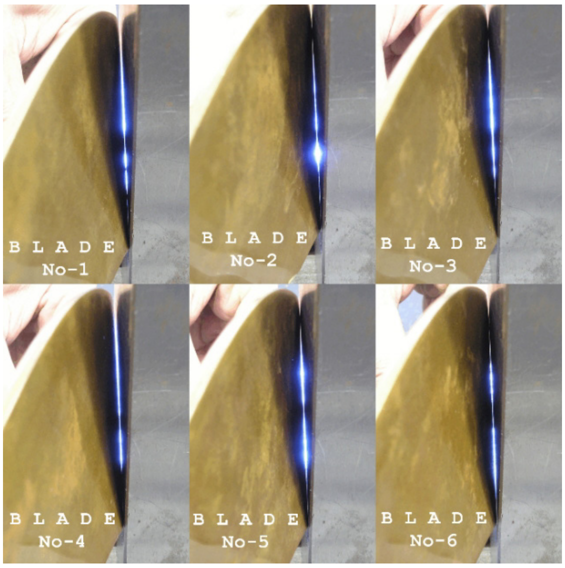


Fig. 2. Visual control of 6 blades trailing edges

Optical scanning of the turbine blade was done in LAZAK labs [10], with 3D-scanner on structured white light. The need to reduce the cost of transportation from Serbia to Slovenia, a visual inspection of all blades was performed in order to select the blade in its best condition. Fig.2. shows this visual control. The most critical part of the blade is the trailing edge. Fig.2. shows clearly trailing edge of the blade no. 6 is the closest to the straight line, hence it is chosen as a representative.

Used scanner is made in LAZAK Lab [10]. It is consisting of 2x PTGray CCD cameras (Grasshopper3 4.1 MP Color USB3 Vision CMOSIS CMV4000-3E5) with 12mm Kowa lenses and a HD DLP projector. The point to point distance at 250 mm FOV (field of view) is 0,12 mm, the accuracy is 0,05 mm at the same FOV. For scanning procedure, we are using FlexScan3D software. The scanning speed is 1.3 seconds per scan. LAZAK scanner is shown on Fig.3.

Fig. 3. LAZAK Scanner

The result of the optical scan of the selected blade is shown in Fig.4. Before the beginning of reverse design, the boundary dimensions given in the drawing were checked, Fig.1. The coordinate system of the blade is set in the manner defined in Fig.1. Inside the CAD model, a sphere of diameter 307,635 mm is set with the center in a coordinate origin. The boundary plane, which should tangent the trailing edge of the blade, set at a distance of 32.2mm from the coordinate origin.

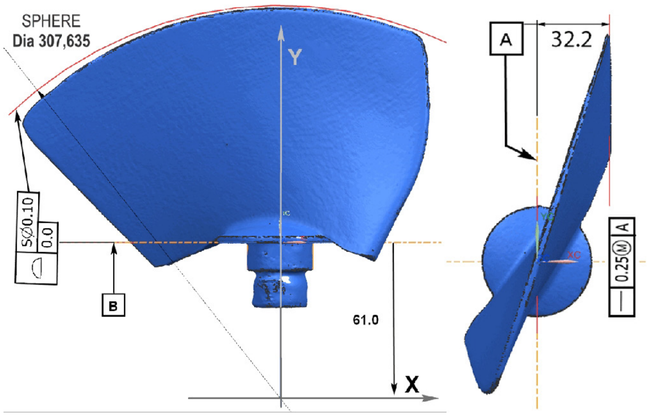


Fig. 4. Scanned Turbine Blade and Boundary Entities

Although manufacturing tolerances are not known, it is noticeable that the deviations of the tip of the blade from the boundary sphere are several millimeters in certain zones. Also, it is noticeable that the trailing edge is not a line, and the end surface of the suction side is not tangent to the boundary plane set at a distance of 32.2mm.

3. RE of Turbine Blades – Related Works

Paper [11] is often cited, and give an overview of the entire RE process applied to turbine blades: from the damaged part, possible contact and contactless scanning methods, and the necessary steps in the modeling process. In this paper, the goal is to create a new blade with milling. Defined necessary RE steps (point cloud, boundary curve, solid model) do not indicate the specificity of the entire class of problem.

Paper [12] defines three steps RE for obtaining a CAD model: first step of the process is scanning the part and generating a points cloud; second step is merging and aligning the CAD model and scanned model. The third step is deviation calculation between the two computer models from the second step. Unfortunately, the authors of the paper do not distinguish the shape error and the position error. In order to get a valid computer inspection, it is necessary to separate the errors of the shape and the error of the position.

In the paper [5], the authors presented the original algorithm describes the segmentation and constrained fitting algorithm implemented on a reverse engineered a sample that was a heavy-duty rotating turbine blade to get the drawing geometry. Particularly important is the segmentation for the zone of the Leading Edge (LE) and the Trailing Edge (TE). After interpolation of circular arcs for LE and TE, the algorithm performs a segmentation separately for the pressure side and separately for the suction side.

In the paper [13], the authors concluded that the use of computerized tomography (CT) did not meet all the measurement requirements and therefore it was combined with other measurement techniques. By combining the optical scanner and the CT, the authors paid special attention to setting the scanners coordinate system. This is extremely important in cases where two or more scanned blades are compared.

The purpose of [14] is to acquire three dimensional profile of a hydraulic turbine runner which cannot operate with full performance by using RE. A point cloud of blades is obtained using a laser scanner. Two dimensional point cloud of meridional contour, blade thickness and blade angles are obtained from digitized CAD model blade. Profile of the runner blade is developed from digitized CAD model. Profile of the runner blade is developed from Two dimensional point cloud of meridional contour, blade thickness and blade angles. Computational Fluid Dynamics (CFD) analyses are carried out in different operating ranges through the three dimensional profile. The reason of the lack of performance in the turbine is investigated in accordance with CFD results.

In the paper [1], the geometric data of the runner were obtained by using simple scanning method in order to identify the most appropriate profile for the blade. The scanning method using a micrometer mounted in a rotating device had a measurement precision of 1 μm therefore the blade coordinates were accurate obtained for profile coordinates and the stagger angles. By comparison of the acquisition data with available theoretical airfoil coordinates available on internet, the authors found an airfoil whose shape is very close to the shape obtained by scanning. After identification of the hydrodynamic profile and the stagger angles for 9 sections of the blade, calculations for verifying the turbine's parameters have been carried out.

Proposed measurement strategy [15] was to reconstruct a Kaplan hydraulic turbine runner. A turbine runner having 4.3m long was measured using a Coordinate Measuring Arm (CMA) with contact probe and samples with point coordinates of the runner were obtained. The authors defined the control cylindrical sections, in which they scanned the geometry of the blade. The water pushes the blades and causes a spinning movement of the runner around the turbine axis.

This is the only correct way of RE of the blade. The redesign of the blade must be carried out in such a way that the blade is designed. The obtained profiles in the cylindrical cross-sections must unwrap into the plane and after that operation their fitting is carried out. This method and the equations (1) of wrapping / unwrapping airfoils were given in [16], published by authors of this paper more than 20 years ago. Fig.5. show the cylindrical section in blade RE process.

$$
\begin{aligned}
X &= R \cdot \sin[(X_T \cdot \cos U - Y_T \cdot \sin U) \cdot 180/(R \cdot \pi)] \\
Y &= R \cdot \cos[(X_T \cdot \cos U - Y_T \cdot \sin U) \cdot 180/(R \cdot \pi)] \qquad (1) \\
Z_{P/S} &= H_P + X_T \sin U + Y_T \cos U
\end{aligned}
$$

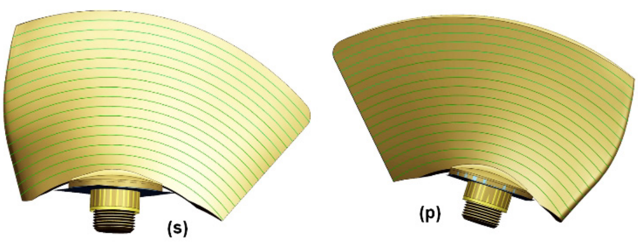


Fig. 5. Cylindrical section: Suction side (s); Pressure side (p)

4. RE of Scanned Turbine Blade

Four tasks for blade redesign were set:

1) Correction of detected deviations from boundary entities.
2) Correcting smoothness and discontinuity on the leading edge and the pressure and suction side.
3) Enlargement / scaling of the newly designed blade geometry to the boundary sphere of the given diameter 310mm
4) Trimming the blade surface within a newly defined hub.

4.1. Work coordinate system setting

The first step in the blade redesign is an alignment of working coordinate system according datum features. The blade is scanned in an arbitrary coordinate system, its position and orientation is not relevant for further work. This step is critical because it will determine the exact position of the boundary entities. The old drawing defines the position of the coordinate system but does not clearly indicate which surfaces are the reference (datum plane, datum axis). Errors made at the very beginning, run through the entire process, leading to the final product. Errors made initially cannot be corrected later, they become systematic errors.

The first dilemma, the orientation of Y axis: the axis of the cylindrical part of the blade or the vector of the flat surface which support the blade? Ideally, these two vectors coincide, but in reality they are not coincidental, especially for blades that have been in exploitation for decades. This dilemma unambiguously indicates the need for proper application of Datum and Datum Systems, defined by ISO [17] & [18]. The method of mounting the blade on the hub determines the choice of the Y axis direction: the axis of the cylinder.

X, Z origin set in the center of the cylindrical part of the blade as defined on the Fig.1, but determining the direction of X axis requires careful analysis. As shown in Fig.2, each blade has trailing edge very deformed. The X axis direction depends on the chosen method of line interpolation. Small thickness of trailing edge requires setting of the maximum material condition, Fig. 4. The trailing edge is a critical blade zone due to risk of damage in manufacturing process. The distance between coordinate origin and line of trailing edge on suction side is informal dimension.

Taking into account the previous explanations, the coordinate system is set in the following way: Y axis perpendicular to the plane of support. Direction X axis determined using the least squares method through the points on the trailing edge of the suction side. The XZ origin is placed at the point of intersection of the axis of the cylindrical part and the plane of the blade support. Y origin is set at 61mm from the plane of the blade support. The orientation of the XYZ axis is determined by the right hand rule, Fig.4.

4.2. Pressure and Suction Side Rapid Surfacing

Scanned Blade is exported as STL file, facet body. Using powerful tools for reverse engineering [9] from initial facet body, CAD model is developed for flow analysis and manufacturing.

Facet Body Curvature [20] creates a color map that differentiates areas of high and low curvature in facet body. This helps to set up a proper patch structure for reverse engineering. Color map with the Extract Feature command allows extract concave, convex, and flat areas and extract borderlines between those areas. Redesign process has been carried out in two basic steps:
(1) Rapid surfacing: base for cylindrical section (Fig.6a)
(2) Detailed surface meshing; leading edge smoothing, trailing edge modification to make tangency with boundary plane, trimming to boundary sphere and hub, filleting, reflection analysis and back if necessary … (Fig. 6.b)

Existing damage on leading edge, trailing edge and on the tip of the blade dictate boundary for rapid surfacing. This boundary does not cover the entire blade, Fig.6(a). After rapid surfacing it is necessary to enlarge and match edges in order to achieve continuity.

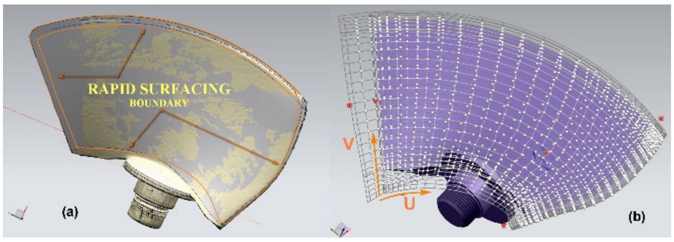


Fig. 6. (a) Rapid Surfacing Boundary; (b) Mesh along U&V parameters

The *Rapid Surfacing* command [20] reverse engineers a facet body quickly, where speed is more important than surface quality. User specified the desired degrees and segments, and create a curve network on the facet body. This curve network generates a G1 continuous surface model of the facet body. Continuity describes the behavior of how curves and surfaces are joined together. The two types of continuity are [20]:

- Geometric continuity, denoted as G0, G1, G2, G3.
- Mathematical continuity, denoted as C0, C1, C2, C3.

Geometric continuity indicates physical continuity between two geometric objects in terms of their properties such as position, tangency and curvature. Mathematical continuity indicates the degree of continuity between two geometric objects in terms of their derivatives. Geometric continuity is less strict than mathematical continuity.

4.3. Trailing Edge Fitting

After all steps, described above, it is possible to remodel trailing edge to tangent boundary plane at define distance, shown on Fig.4.

Trailing edge is modified in such way to make tangency with boundary plane at specified distance. Continuity G0&G1 must be satisfied. Movement of trailing control nodes, affects the surface changes in several rows in “u” parameter direction, Fig. 6b.

Fig.7. shows a scanned trailing edge and new one, fitted according to a design request. Large deviation are results of deformations and damages occurred during 4 decade of exploitation.

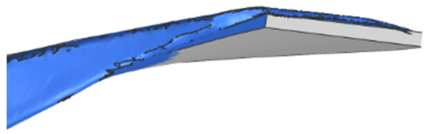


Fig. 7. Trailing Edge Detail: Facet Body (Blue); Fitted Trailing Edge (Gray)

4.4. Trimming Lower Side of the Blade

The previous activity did not modify the lower side of the blade, the boundary zone towards the hub. Before determining the trimming limit, the blade is scaled to the boundary sphere diameter of 310mm Fig.8(a), as defined by the design requirement.

The maximum angle of rotation of the blade is 10 degrees, and for this reason the boundary angle defining the trimming limit set to 12 degrees, Fig.8(b).

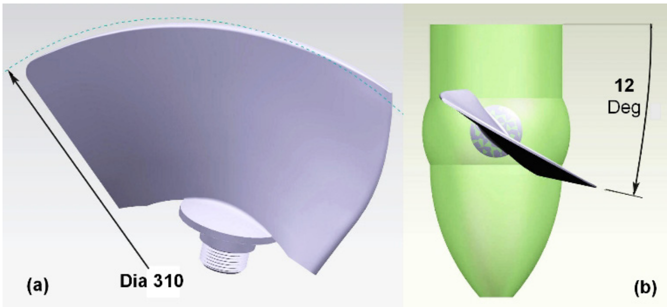


Fig. 8. (a) New Boundary Sphere Dia. 310mm; (b) Limit of Angular Position

The lower side of the blade is trimmed exactly to the hub for this position of 12 degrees. This provides a gap between the blade and the hub for all angles of rotation less than 12 degrees. Practically, the blade should not rotate more than 10 degrees because of risk of encroachment.

4.5. Smoothness Verification

The final check of the reverse design of the blade involves checking the smoothness of the surface of the pressure and the suction side. Reflection give quick visual feedback as to the quality of the surfaces, surface irregularities and discontinuities will be readily apparent [21].

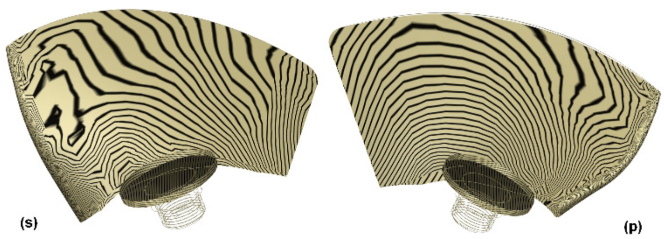


Fig. 9. Reflection: Suction side (s); Pressure side (p)

Using the reflection command, user is able to 'eyeball' what type of continuity have between surfaces.

Fig.8 shows the smoothness check using the option *Reflections* [20]; on the Fig.9(s) suction side and on Fig.9(p) pressure side.

Design validation will be done by flow analysis using one of the specialized programs for this purpose (e.g. Fluent). This activity is planned to be carried out in the near future.

5. Conclusion and Future work

In this paper, we showed RE application in small turbine blade modelling as a novel concept by scale. Geometric reverse engineering has been extended to capture the shape essence of the physical product, manufacturing processes as well as digital product within a lifecycle perspective. Shape segmentation and shape/feature recognition are fundamental problems in shape processing for geometric reverse engineering in this case. Through the discrete curvatures, a novel framework has been proposed and successfully tested on turbine blade.

The limitations of these methods were considered and compared with other approaches. Foremost among these limitations are:

- non-smoothness of the boundaries of the shapes,
- sampling from rough surfaces,
- lack of external source of information and knowledge.

Future work in this subject will be:

- data mining for shape generation, and
- RE topology optimization by additive manufacturing.

Finally, cyber-physical manufacturing can be big potential for this subject [22], in the future.

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