Application of Reverse Engineering method to model eroded Francis runner.

Ashish Sedai$^{1,3}$, Biraj Singh Thapa$^{1,2*}$, Bhol a Thapa$^{1}$, Aman Kapali$^{1}$, Zhongdong Qian$^{2}$ and Zhiwei Guo$^{2}$

$^{1}$Turbine Testing Laboratory, Kathmandu University, Kavre, Nepal
$^{2}$State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
$^{3}$Department of Mechanical Engineering, Chandigarh University, Mohali 140413, Punjab, India

* Corresponding author: bst@ku.edu.np

Abstract

Damage of runners and other components of hydro turbine by sediment erosion and cavitation erosion is an inevitable problem associated with hydropower established in a region with mountainous topology. The paper attempts to investigate the suitability and sustainability of the reverse engineering method for the design of the eroded Francis runner. This manufacturing technology is in a progressive phase of development in various parts of the world, so research scholars have been constantly working on the concept to increase the speed and efficiency of the method. The case investigation was conducted on Puwa-Khola 1HPP eroded Francis runner. The paper investigates reverse engineering design methodology of the eroded runner and discusses scope and limitation in the utilization of method at Hydropower sector. Also, the paper suggests suitable 3D scanning techniques, reverse engineering tools, and optimization methods for obtaining mathematically sound models without any hydraulic profile deviation between actual and reversed engineered model.

Keywords: Reverse Engineering, 3D Scanning, Sediment erosion, Cavitation.

1. Introduction

With an increase in automation and the standard of living use of electricity has increased significantly. In the context of Nepal, it has a high potential of water resources, covering 395,000 ha (48%) area within 45,000 km in length of 6000 rivers with 45,610 MW feasible hydropower generation [1]. Over 90% of the country’s total electricity generation is from hydropower plants and the country’s economy is highly reliable in hydroelectric power generation and its sale to its neighboring countries [2]. However, lack of proper infrastructure is a challenge in the transportation of such energy. Nevertheless, if the country can develop proper infrastructure for the supply of electricity to its neighboring countries revenues made through exports could raise the Nepalese economy to heights in no time [3]. Developing countries like India, Bangladesh, and Pakistan are close to Nepal and the demand for electricity in those countries is escalating at a great pace [4]. Nepal being rich in water resources, capable of producing 45,610MW [1] that could easily supplement the demand in these south Asian countries and improve the overall economy of the region. Nepal has made slow progress in the development of hydropower with less than 1 GW installed capacity within the 100 years of its history. However, there has been a rapid increment in the construction of new power plants. Table 1 shows the current status and future development trends of hydropower in Nepal. With almost 25 GW of new hydropower projects at some stage of the development, Nepal has a very promising future of hydropower technology.
Table 1. Current status of hydropower in Nepal adapted from [1]

| S.N. | Summary status of hydropower development | No. of projects | Capacity (MW) |
|------|------------------------------------------|----------------|--------------|
| 1    | Completed projects                        | 80             | 937.31       |
| 2    | Projects under construction               | 57             | 4935         |
| 3    | Issued construction licenses for generation | 148         | 4322.59      |
| 4    | Issued survey licenses                     | 289            | 13397.85     |
| 5    | Application received for survey licenses   | 23             | 2084.16      |
|      | **Total (2-5)**                           |                | **24,739.56**|

Asia region suffers from sand erosion due to the relatively young geological formation and heavy precipitation in a short time interval causing floods. In the central Himalaya and Ganges plain, more than 80% of the annual rainfall occurs during the Indian summer monsoon season (May–October) [5]. This causes a drastic increase in sediment concentration in rivers every year. Hence, the hydropower plants in these regions are reported to be severely hit by the erosion of turbine components due to hard sediments. Several studies have shown severe effects of such erosion on the performance and life of the turbine with significant financial losses [12]. This has created a need for technological advancements and innovations for effective operation and maintenance of mechanical equipment in sediment-laden projects.

2. Background of study

Francis turbine is the most widely used type of hydro turbine in Nepal. Until now the design and development of Francis turbines have not taken its swift growth. This may be due to a lack of sufficient competence to exploit its resource or maybe use of a similar conventional design approach for both bigger hydropower projects and smaller hydropower projects. Another challenging issue in the development of Francis turbines is complex hydraulics due to steeper rivers consisting of a large number of sediment particles. Figures 1 and 2 show the effect of cavitation and material erosion in the turbine runner due to excessive sediment inflow.

![Figure 1. Cavitation erosion in runner [6]](image1.png)  
![Figure 2. Sediments Erosion in runner blade](image2.png)
The failure of Francis turbine is normally due to sediment erosion, cavitation, fatigue of material, and mechanical defect. Sediment erosion occurs due to sediments present in the river water due to glaciers of the Himalayas, regular monsoon rain, and general topography. The process of erosion of runners is influenced by the sediment concentration, average speed of the particle, particle characters: (shape, size, and hardness) and frequency of contact between the particle and surface of the runner [7].

Equation (1), shows the relationship between wear and velocity of a Particle [8]

\[ \text{Wear} = a \times (\text{Velocity})^n \]  

Equation 1 suggests wear in a material is directly proportional to the velocity of particles striking on the material. Where \( n \) is the exponent of the flow characteristics and material properties. Thus, the erosion of turbine material is exponentially proportional to the flow velocities. As the fluid flow inside the turbine is high, the sediment erosion cannot be eliminated completely. However, several methods have been practiced to minimize the erosion of the turbine material due to sediments in the water.

Brekke proposed the design criteria for minimizing sediment erosion effects with the applications of ceramics as coating materials [10]. Thermal sprayed tungsten carbide cobalt-chromium coating WC-CoCr [9] is adopted to minimize the erosion effect. The Turbine Testing Lab at Kathmandu University is involved in the design, development, and testing of hydro turbines with better sediment handling capabilities [11] [12]. Similarly, researchers in the Turbine Testing Lab have proposed Francis turbine without the guide vane for minimizing sediment erosion losses [13].

Cavitation is another phenomenon that causes mechanical damage to turbine components. Cavitation is rapid formation and collapse of vapor bubbles within a liquid when static pressure becomes smaller than the liquid’s vapor pressure. The continuous breaking of water bubbles when water bubbles traveling from low pressure to high pressure can cause major damages on the surface of the runner. Figure 3 represents the damage in Francis runner due to cavitation erosion.

The bubble generated in the low-pressure region when traveling from the low-pressure region to the high-pressure region causes shock wave generation, vibration and undesirable sound. For avoiding such losses, the turbine should be designed with optimal design cavitation value. However, avoiding it completely is not possible. The combined effect of cavitation and sediment erosion can be very complex and posses potential incomplete removal of the turbine’s components over a long-run period. This paper presents the application of reverse engineering method in the Hydropower sector of Nepal for speedy maintenance of eroded Francis runner and rehabilitation of projects.
3. The case study

To investigate the feasibility of the reverse engineering method for the re-modeling of Francis runner, a case study is conducted on the eroded runner of Puwa-Khola 1HPP. The case study involves 3D scanning of the eroded runner and processes of obtaining a CAD model from 3D scanning of the eroded runner of Puwa Khola 1HPP, Run of River type, located at the eastern part of Nepal, Ilam with an installed capacity of 6.2 MW and annual design generation of 48 GWh was commissioned in 1999 AD. It was jointly developed by the Government of Nepal and NEA at a cost of USD 15.7 million. The station has two units each with 3.1 MW [15]. Table 2 presents the features of the Puwa Khola 1HPP.

Table 2. Salient features of Puwa-Khola 1HPP

| Type                        | Francis                  |
|-----------------------------|--------------------------|
| Shaft Position              | Horizontal               |
| Nominal Speed               | 1000 rpm                 |
| Minimum Turbine Flow        | 860 lps                  |
| Maximum Efficiency          | 92.2 %                   |
| Runner Diameter             | 572 mm                   |
| Inlet Spiral Case Diameter  | 643 mm                   |
| Water Pipe Diameter         | 800 mm                   |
| Runner Material             | Stainless Steel 134, machined |
| Runaway Speed               | 1726 rpm                 |
| Turbine Setting             | -1.50 m below TWL        |

Figure 4 represents the eroded Francis runner of Puwa Khola 1HPP. The runner was observed with damage, mainly on the blade section. The reason for the damage could be sediment erosion, cavitation, or fatigue failure. The reverse engineering method was applied in this runner. The 3D scanning of the runner was conducted at Turbine Testing Lab, Kathmandu University during a workshop organized jointly by Kathmandu University and Wuhan University.

3.1. Reverse engineering Method

Reverse engineering is a non-conventional type manufacturing process that involves the deconstruction of an existing component to extract design and reconstruct it with additional information to enhance the performance of the component. Reverse engineering reduces the manufacturing time and cost for the industry. The method is very useful when the original blueprints of the product are lost or destroyed, and the model requires speedy maintenance. The reverse engineering method helps in understanding existing models, maneuvers, and discover the
vulnerabilities of products. Also, the method is suitable for creating a reliable CAD model for future reference and in the optimization of models based on the base design. Basic steps of reverse engineering are:

3.1.1. Capturing data

- A 3D scanner is used to extract design information from the physical model and convert it into a computer-readable file. The data acquisition is generally performed using a laser scanner, coordinate measuring machine (CMM), and industrial computed tomography (CT) scanner that converts the physical model dimension into graphical format.

3.1.2. Redefining the model

- In this part of the reverse engineering method, CAD software like Solidworks, Catia V5 etc. are used to remodel the product.
- Further, the reverse-engineered model is validated and optimized using CFD software.

3.1.3. Manufacturing

- The final step of the reverse engineering method is manufacturing. The Optimal and CFD validated reverse-engineered model gets industrial ready for the manufacturing process.

![Flow chart process of reverse engineering](image)

**Figure 5.** Flow chart process of reverse engineering [16]

3.2. 3D scanning of runner

3D scanning is an important part of the reverse engineering method. The method helps in extracting physical models into a computer readable format using either contact or non-contact type scanners. A polymesh of the model is extracted using point cloud data acquisition techniques. The polymesh, NURBS (Non-uniform rational B-spline) curves, or NURBS surfaces are exported to CAD model for
the re-modeling purpose. 3D scanning helps in the measurement and extraction of complex geometrics of the model into a graphical format which increases the speed of manufacturing and makes the whole process lot easier and cost-efficient.

![3D Scanning Techniques](image)

**Figure 6.** Types of 3D scanning technique[17]

Figure 6 shows the classification of 3D scanning technique. 3D scanner used for our investigation was non-contact type and data acquisition were done using a laser scanner. The model of the scanner used was Creaform EXAscan and the software used was VXelem. The steps followed in 3D scanning are presented in Figure 7.

![Steps involved in 3D scanning of runner](image)

**Figure 7.** Steps involved in 3D scanning of runner

3.3. Reverse engineering design methodology
The basics of the methodology are shown in Figure 9. Firstly, part digitization is done in the existing runner geometries performing surface approximation and creating a CAD model of the runner. Meridional contour is determined from the extracted CAD model using a reverse engineering tool. Blade angle and thickness of the blade are defined according to the original dimension of the runner. However, not every time, the blade of the runner is perfectly extracted into the CAD model because of the complexity of the structure. So, obtaining a mathematically correct blade might not be always possible with this technique. Figure 8 represents a detailed reverse engineering design methodology for eroded Francis runner.

**Figure 8.** Steps of reverse engineering design adapted from [18]

Figure 9 is adapted from the International Standard code book for model acceptance test of the hydraulic section IEC 60193[19] the standard code is primarily applicable for checking similarity between prototype and the model for Francis runner. These similarity check rules are applied in resetting the eroded Francis runner. The method helps in positioning the reference surface in the CAD model over which a template can be drawn for the re-modeling of the runner. The IEC 60193 code provides step by step technique to determine the location for checking outlet width, extracting dimension of hub, shroud, and overall blade profile. The blade inlet profile is determined by checking at least at two sections, where inlet section extends from nose of blade to reference diameter along both pressure and suction side, inlet blade angle is measured by checking the same section as blade profile as shown in figure 9. Similarly, the blade outlet profile is determined by measuring at least at three sections where outlet section extends from the trailing edge of blade to the reference diameter along both sides of the blade.

**Figure 9.** Location for checking outlet width and blade profiles [19]
3.4. Results from 3D scanning

Figure 10 represents meridional contour on section plane to create a template outline for the reverse engineering method. Figure 11 represents a 3D scanned runner image of Puwa Khola 1 HPP. The scanned image was not exactly as a physical model due to complexity of the structure and limitation of the scanner. With reference to the flow chart in figure 6, after successful acquisition of 3D model, STL file was extracted to reverse engineering tool Ansys Spaceclaim where firstly extra material from the model was removed and smoothen. Meridional contour on section plane was obtained to investigate any missing parts in the model and with reference to IEC 60193[19] outline template was created and extruded as required and finally, dimensions were matched with the physical mode to check the accuracy. Figure 12 represents the progressive stages of re-modeling of Francis runner using a reverse engineering tool.

![Figure 10. Meridional contour on section plane [18]](image1)

![Figure 11. Scanned runner blade image](image2)

![Figure 12. Reconstruction of Francis runner using reverse engineering tool](image3)

Figure 13 (a) represents the image of a 3D scanned model of the runner. Figure(b) represents the meridional contour of the runner obtained after removing extra materials from the model. Figure(c), (d), and (e) represents the development of hub, shroud, and blade of the runner respectively. For obtaining diameter of hub, shroud and blade portion line template were created from the meridional contour of the 3D scanned model. Figure(f) is a single blade image developed and modified using the RE tool. Figure (g) is the final product obtained using the RE tool Spaceclaim. Figure (h) and (i) is the rendered image of a reverse-engineered model obtained using Solidworks software.
3.5 Scope and Limitation

Sediment erosion is a major problem in Hydropower established in a region with mountainous topology due to high concentrations of sediments in a river. The possibility of damage to runners and other components are quite frequent for such established hydropower plants. So far, the reverse engineering method was not investigated in the context of the Nepalese hydropower sector for repairing and maintenance. This study suggests that, with the aid of appropriate 3D scanning tools and RE tools, quick repairing and rehabilitation of damaged components of hydropower plants is feasible and effective. This case study where most of the parts of the runner were damaged, the reverse engineering tool was found efficient even in such extremity. However, the validation of the re-modeled geometry is a necessary part of the reverse engineering process, which further works and beyond the scope of this paper.

The tool used in reverse engineering of Francis runner is Ansys Space claim. The results presented in this paper is part of research on “Design and optimization of Francis runner using reverse engineering method”. To the knowledge of this research team, it is the first effort for 3D Scanning and Reverse Engineering of Francis Turbine in Nepal for the maintenance of damaged turbine components. Kathmandu University, Turbine Testing Lab has established competence for 3D Scanning as a part of the technology transfer and competence building collaboration program between Kathmandu University and Wuhan University to sustain the use of reverse engineering methods in the rehabilitation of turbines in the Nepalese hydropower sector.

4. Conclusion

The reverse engineering technique is found to be feasible and efficient to be utilized in the reconstruction of eroded Francis runners. Damage to the runner and another component of the turbine is prominent in hydropower plants established in a region with mountainous topology due to large concentrations of sediments in rivers. The application of the technique in the hydropower sector can reduce time and cost for the timely maintenance of eroded turbine components. It was found that reverse engineering tools are very efficient for the re-modeling of the Francis runner. However, achieving a model without hydraulic deviation between actual and reverse engineered models an additional optimization software should be implemented. The determination of the blade design parameters is a vital part of the whole process. Meridional contour, blade angles, and blade thickness distribution are the design parameters and they are necessary to be obtained into analyzable blade geometry.

Validation check of the reverse-engineered model is the next part of the research and can be identified with the application of optimization software to ensure the model without any hydraulic profile deviation from the actual model. This technology is believed to be very beneficial for maintenance and quality assurance of eroded turbine components and in improving the efficiency of maintained/rehabilitated turbines.

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