

# Application of Reverse Engineering Method on Francis Turbine Runner Using 3D Scanning Techniques

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**Abstract**—The reverse Engineering Technique uses 3D scanning device that capture three-dimensional data into a digital format. The physical geometry is converted into computerized forms to carry out product development, design optimization and useful computational analysis. Within all reverse engineering techniques this method has proven to be more valuable to acquire 3D measurement of physical objects with higher accuracies, even for complex geometries. This paper presents reverse engineering approach for the remodeling of 3D Francis turbine runner. The scanned digital file of runner 23MW, which is one of the units of Marsyangdi Hydropower powerplant (69 MW) has been used as input in the modeling. The result from the 3D model developed using reverse engineering approach showed relatively close geometrical similarities. The deviation in the radii  $r_{2i}$ ,  $r_{1i}$ ,  $r_{1a}$ ,  $r_3$  and blade thickness is 5.37mm, 2.4357mm, 3.5mm, 4.11mm and 2 mm respectively. The final model is validated by comparing the torque developed on rotating blades for the data input obtained from the power plant. The power obtained from the (Computational Fluid Dynamics) CFD analysis is 26.71MW. Using this technique, further analyses can be carried out for design optimization of the runner for maximizing efficiency, minimizing erosion and cavitation, as well as increasing the dynamic stability of the turbines.

**Keywords**—Reverse Engineering, Modeling, CFD, Francis Runner, 3D scanning

## I. INTRODUCTION

Manufacturers of modern world are obliged to deliver more competitive goods and services with better quality and cost efficient. With development in manufacturing industries, 2D or 3D CAD (computer Aided Design) model has become important. The new processes like reverse engineering are efficient to solve the problem of competitive market, to deliver product with short lead time and better feature. The Physical parts or whole geometry are digitized to develop a virtual model using reverse engineering approach. It is possible to regenerate an existing part by recreating its surface geometry in a 3D digital file format with the help of a scanner or measurement device. This technique allows us to design a CAD

model of a part that lacks design data or prone to go through number of design changes.

Reverse engineering techniques has been used to redesign the hydraulic turbines. Among different types of hydraulic turbines, Francis turbines are the popular type due to their wide range of head and flows. Different research has been done to in the field of reverse engineering application in Hydraulic turbines. Modified adaptive model-based digitizing process (MAMDP), a reverse engineering approach has been used to design 3D geometric turbine blades [1]. Reverse engineering Technique has been used in Francis runner in which geometry has been scanned through Photogrammetry [2]. Reverse engineering Methodology has been used to obtain the CAD models of Francis turbine which later used to generate fluid volumes and for CFD analysis [3]. 3D scanning and Reverse engineering process has been used for obtaining flow models and optimizing the turbine efficiency [4]. Geometric reconstruction methodology has been developed including 3D digitalization process [5]. The reverse engineering method and application of particular method has been explored to remodel the eroded Francis turbine runner [6]. Reverse engineering methodology has been developed for redesigning of turbines for the rehabilitation of existing power plants [7].

## Reverse Engineering Process

Reverse engineering is a progressive type manufacturing process which covers the deconstruction of an existing parts to extract design and redevelop it with additional information to enhance the performance of the component. Generally, there are three major steps in reverse engineering approach that include scanning phase, point processing phase and solid modeling. M.Chang further classify these steps as data acquisition, preprocessing, triangulation, feature extraction, segmentation and surface fitting which are displayed in Figure 1 below. [8] [9]. During data acquisition phase, the data related to geometric aspect of physical object is gathered with the help of scanning. In this phase suitable scanner (laser or CMM) are used to

scan the physical model so as to collect information regarding physical feature like curves, slots. Data from scanning are processed in order to delete noise and minimize the number of data points. The cloud points are minimized using Filters. Merging of multiple scan data sets can be done. Different commercial software can be used for point processing. The process that includes formation or division of point data into triangles is termed as Triangulation. Triangular mesh can be created using a suitable algorithm. A set of characteristics, or image features are clarified in feature extraction, which shows the information that is essential for analysis and classification. Also, dynamic fitting algorithms are applied to generate the surface that represents the 3D information that lies in the set of point cloud data. Segmentation is the process in which triangular mesh are disassociated into sub-meshes. At last, the 3-dimensional CAD model is obtained.

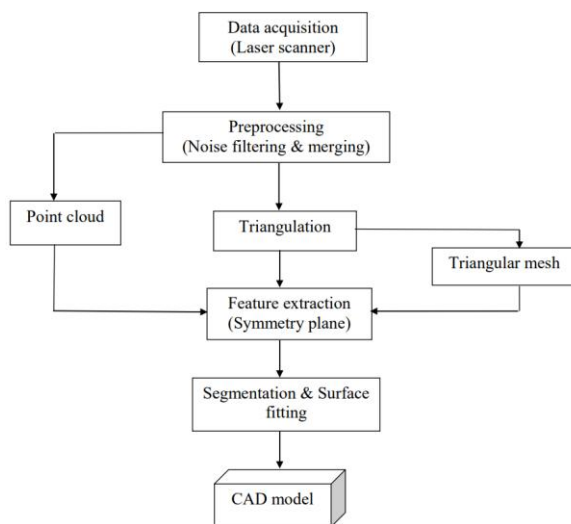


Figure 1 Flow of Reverse Engineering process (Adapted from [8])

### 3D Scanners Types and Scanning Techniques

In the modern industrial sector, the application of 3D scanning industry is expanding rapidly. 3D scanning is to generate three-dimensional replica out of data collected by scanner from any object. 3D digital model is developed as a point cloud which consists information of object's shape. Generally, the two types of scanners are contact type and non-contact type which are represented in Figure 2.

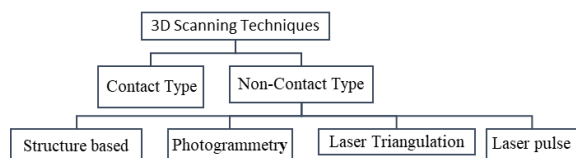


Figure 2 Classification of 3D Scanning Techniques (Adapted from [10])

Contact scanners comprises contact probe which travel along silhouette of physical object. Usually, the probe is made to move over surface to obtain the

information. Co-ordinate measuring machine (CMM) is one of common contact scanner. The non-contact types are those which utilizes optics, lasers and charged couple device (CCD) sensors to collect the data. Using triangulation principle, light grid pattern projections is used and synchronized with the camera to obtain surface properties of the object in structured light 3D scanner method. Light modulators are used to produce pattern of light. In structured light 3D scanner, displacement of stripe is translated to 3D coordinate of the bodies. Laser triangulation technique applies the triangulation principle to measure distances between laser source and point on surface. Detector placed such that diffused reflections are detected and that source object and detector forms a triangle [10]. Laser triangulation 3D scanner are used in entertainment industry, reverse engineering. Photogrammetry technology are used to reveal geometric properties of object through photographic images. Number of images of an object through various views with common reference point in each photograph are taken. Then pictures can be developed into 3D model through photogrammetry software. Photogrammetry is used for topographic mapping. Laser Pulse based 3D scanning depends on timing of laser to hit the target and return. Distance can be calculated with available speed of light and time taken by laser. These scanners are used to scan large scale scanning.

The objective of this paper is to identify feasibility of reverse engineering technique to remodel the Francis turbine runner. The model is compared with industrial drawing to ensure geometrical similarities. The CFD analysis has been done to the runner fluid domain to calculate the Hydraulic power so as to compare with rated power of actual turbine. The scanned file was not good enough to develop proper surface out of it. The reverse engineering tool on Ansys Space claim is used. The measurement done for comparing with the drawings of meridional contour are limited. Due to large size of geometry and not enough computation power, proper meshing of geometry is still lacking. The mesh used is poor.

## II. CASE STUDY

To study the possibility of the reverse engineering method for remodeling of Francis turbine runner, a case study is taken as one unit runner 23 MW of Marsyangdi Hydropower station of installed capacity 69MW which is located at Aanbukhaireni, Tanahu, owned by Nepal Electricity Authority [12].



Figure 3 Marsyangdi Hydropower Turbine runner

Table 1 Salient feature of Marsyangdi Hydropower

Type	Peak-run-off-river
Rated net Head	90.5m
Rated Discharge	30.5m <sup>3</sup> /s
Turbine	3 sets
Turbine type	Francis
Rated speed	300 rpm
Type of generator	Vertical shaft synchronous

Reverse engineering Design Methodology

The basic reverse engineering design methodology is shown in Figure 4. This methodology can be applied to redesign the existing turbine runners. As shown in figure 4, part digitization is the first step in which primary point cloud data are obtained to be able to model turbine runner. Surfaces are generated using point cloud data and then solid model of one of the blades is generated and then blade is reflected to develop whole turbine geometry. Meridional contour is a two-dimensional profile that determines the boundary of the blade geometry. Meridional contour is defining as the runner blade profile are projected in radial plane. The Blade angle and thickness of blade are defined as per original dimension of the runner [7].

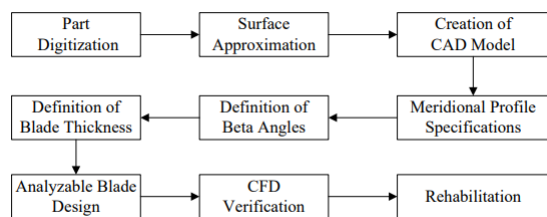


Figure 4 Flow of Reverse engineering design (Adapted from [7])

A. 3D scanned data

3D scanning is one of the essential steps in reverse engineering method. Non-contact type 3D scanner was used and data acquisition were done using a laser scanner. The model of scanner used was CreaForm EXA Scanner as shown in Figure 5(b) and 5(c). These are handheld laser scanner which create 3D image through triangulation mechanism. In triangulation mechanism, a laser dot or line is

projected in turbine blade component from scanner and sensor measures the distance to the surface. The software called VXelements enables 3D scan data to use directly in CAD software. Figure 5 (d) represents the scanned STL file which is ready for 3D modelling.

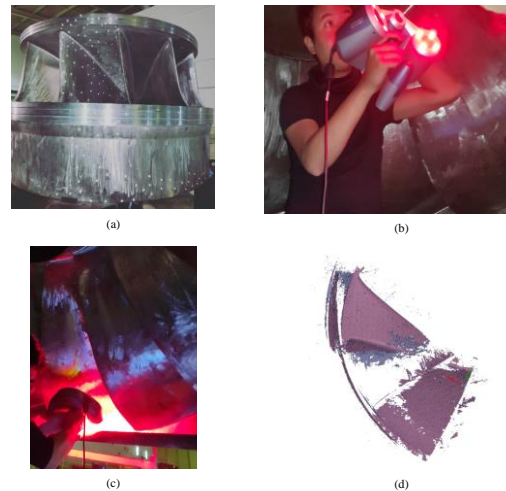


Figure 5 (a) points coated for laser scanning technique in the turbine runner, (b) and (c) CreaForm EXA scanner used for scanning, (d) scanned STL file

B. Remodeling technique adopted

ANSYS SpaceClaim software was used for remodeling of 3D geometry from scan STL (STereoLithography) file. Figure 6 shows the steps followed during remodeling of Francis turbine runner. Figure 6(a) represent the STL file. Initial file was full of voids and outstretched surfaces. Except the pressure side, suction side, hub and shroud portions of STL file, all other were removed. Orientation of STL file is needed before generating surfaces. Using Orient mesh tool specific surface can be oriented. Figure 6(b) represent the orientation of STL file along Z axis but still there is no origin for the central axis. With reference diameter from drawing runner center was located. After finding the world origin of object whole mesh should be oriented to that origin. Figure 6(c) shows the use of planes on surfaces. Due to number of voids in the surface skin extract tool could not be generated. Thus Figure 6(d) shows the curves generated by planes added in the surface using surface Extract tool. But curve should be fitted so that curve can maintain its tangency. It can be done using Fit Curve tool as displayed in Figure 6(e). Figure 6(f) shows the curve generated in each blade portion. Then each small part of curve can be changed into surfaces used Fill tool. Figure 6(g) shows the use of Fill tool in curve of blades. Now with thickness equivalent to the drawing was given to the both blade profiles as shown in Figure 6(h). Then, the whole blade was checked to remove sharp edges and small faces. 13 number of similar blades were developed along the axis which gives the runner



blade portion. For the hub and shroud, similar process was applied. Lines coincide with the portion of both hub and shroud were taken and enclosing them gives the surface. Thus, surface was revolved full along axis so as to give the shroud and Hub section along with the blade. The runner formed can be seen in Figure 6(i).

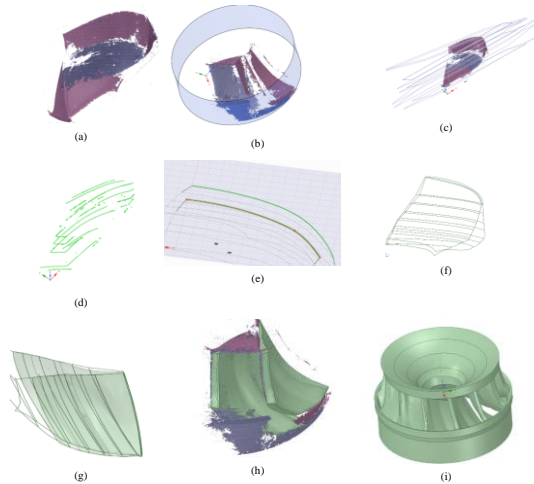


Figure 6 Remodeling Technique adopted to remodel the Francis runner

C. Geometry similarities

IEC 60193 [13] is used to find possible location of runner to be measured for geometrical similarity. The measurement of solid remodeled geometry is done through Measure tool in ANSYS SpaceClaim. The measurement was compared to that of the available drawing. Radii represented as  $r_{2i}$ ,  $r_{1i}$ ,  $r_{1\alpha}$  and  $r_3$  at four locations is measured. Similarly, minimum and maximum blade thickness was compared to available drawing. Only blade was taken and lines are plotted to create contour on the central plane. Figure 7 represents the contour taken at central axis where at four different radii are measured. Figure 8 (a) shows four radii to be measured and Figure 8(b) is the snap of Industrial drawing that shows the value of different radii to which the radii of remodeled geometry is compared. Table 2 represent the parameters which are compared along with the deviation in measurement. The geometry remodeled still do not have smooth edges and surfaces due to which there is still noticeable deviation in the measurement.

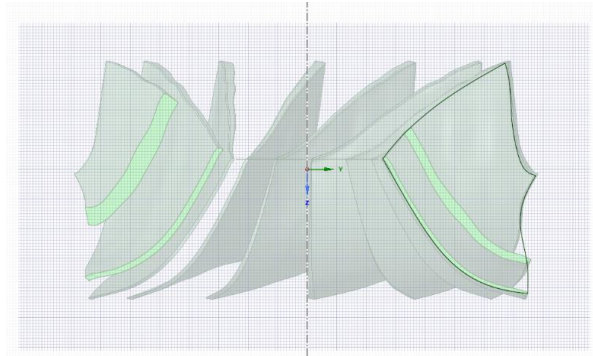


Figure 7 Contour for the radii measurement

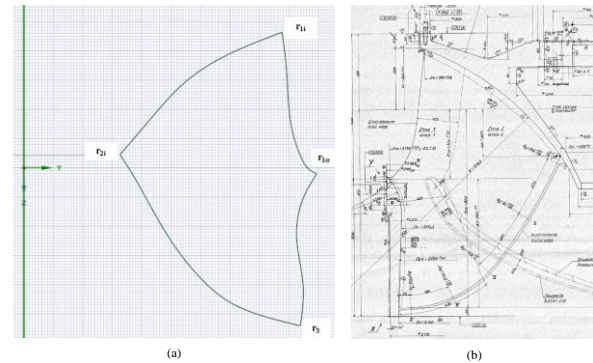


Figure 8 (a) Four radii to be measured (b) Drawing that shows the value of radii for the comparison (adapted from [14])

Table 2 Deviation in Measurement

Parameter measured and compared	Deviation (mm)
$r_{2i}$	5.37
$r_{1i}$	2.4357
$r_{1\alpha}$	3.5
$r_3$	4.11
Maximum blade thickness	2
Minimum blade thickness	2

D. CFD verification

i. Francis turbine model

To study the fluid flow through turbine runner, complete runner passage way has been considered which is shown in Figure 9. It consists of 13 Blades. Moreover, three-dimensional discretization has been done which is based on finite volume method (FVM) provided by the ANSYS CFX software.

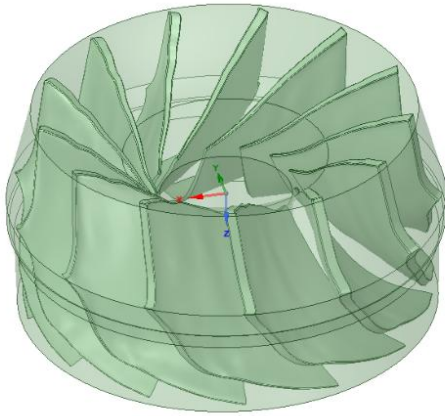


Figure 9 Francis Fluid domain

ii. Mesh generation

3D tetrahedral unstructured mesh has been employed in the above computational domain as shown in Figure 10, due to its flexibility while solving complex and large geometry. Total computational mesh consists of 18.38 M elements, default inflation. The limitation of this project is most of parameters during simulation are taken default due to large size geometry.

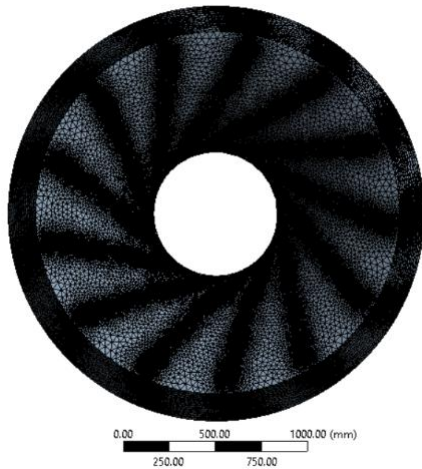


Figure 10 ANSYS CFX Meshing

iii. Mathematical Model

In the fluid flow analysis of the domain, the continuity equation and Reynolds averaged Navier-Stokes equation for an incompressible flow has been used in the following form [14].

$$\frac{\partial U_i}{\partial X_i} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial X_j} + \frac{1}{\rho} \frac{\partial P}{\partial X_i} - \frac{\partial}{\partial X_j} \left( \nu \left( \frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i} \right) - \tau_{ij} \right) = 0 \tag{2}$$

Where  $\nu$ ,  $v$ ,  $p$  and  $\rho$  are kinematic viscosity, velocity, pressure and density respectively and  $\tau_{ij}$  is the mean viscous stress tensor component. It is also called as

Reynolds's stress tensor. The turbulent effects on the flow field are through the Reynolds stresses  $\tau_{ij}$ , which are calculated from the turbulence k- $\epsilon$  model. Turbulence k- $\epsilon$  model is the often-used closure model while modelling turbulent flow. The code uses unstructured finite volume approach, except at the boundaries of the domain, to convert the Reynolds-averaged Navier-Stokes equations to algebraic equations that are further solved numerically.

iv. Boundary condition

The steady state incompressible fluid flow in circumferential direction of turbine runner is used for the computation. As per the salient feature of Marsyangdi Hydropower, inlet boundary conditions of mass flow rate and outlet pressure condition were given. Assuming the Guide vane angle as 17°, the radial and tangential component was taken.

Table 3 Boundary Conditions

Inlet Boundary condition	Inlet Mass flow rate: 30500kg/s Flow direction Radial component -0.292372 m/s Tangential component -0.926305 m/s Axial component 0 m/s
Outlet boundary condition	Outlet 1 atm pressure
Blades, hub, shroud	Rotating, No slip wall

v. Velocity distribution

From CFD analysis for specific operating conditions, velocity streamlines in the fluid domain are obtained as shown in Figure 11. The symmetrical flow can be seen in the runner inlet, which is resulted from the uniform flow distribution of the runner inlet. There is almost radial flow direction at the inlet. There is certain rise in magnitude of velocity near the trailing edge due to decrease in area between blade and the ring. There are still some irregular streamlines which is maybe due to improper fluid domain.

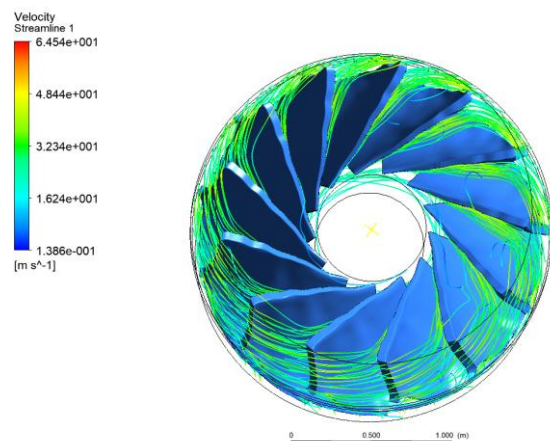


Figure 11 Velocity Streamline

vi. Hydraulic power calculation

The hydraulic power for the runner is given as equation 3. where the torque ( $\tau$ ) is -850177 and angular velocity ( $\omega$ ) is given by -31.42 rad/s.

$$P = \tau \times \omega \quad (3)$$

The rated power for single unit of Marsyangdi Hydropower project is 23 MW. From CFD analysis the power obtained is 26.71 MW.

### III. CONCLUSION

Reverse engineering method is found to be practicable to remodel the Francis turbine runner. Starting with STL file of scanned surface, the runner including blades, hub and shroud were remodeled. For geometrical validity, the radii at different locations were compared to that of available drawing. The deviation in  $r_{2i}$ ,  $r_{1i}$ ,  $r_{1\alpha}$ ,  $r_3$  and blade thickness were 5.37 mm, 2.4357mm, 3.5 mm, 4.11mm and 2 mm respectively. From the CFD analysis of Francis runner domain, Hydraulic power was calculated as 26.71 MW and observed that the power is nearly greater than single unit rated power of Marsyangdi Hydropower which is 23 MW.

This paper focused on viability of reverse engineering technique in remodeling, geometrical validation and CFD applications of Francis Turbine runner. Also, damage to runner blades and other component due to cavitation are prominent in most hydropower turbines, application of this technique helps in maintenance of eroded runners or other complex geometry with in short period of time. This technique can be applied to reveal the complex designs of Turbines and other related components. In future, proper reverse engineering methodology can be developed to redesign the turbine for the rehabilitation of existing power plants. With CFD application further analysis can be carried out as design optimization of runner for maximizing efficiency, minimizing erosion and cavitation as well as increasing the dynamic stability of the turbines.

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