Optimized Design of Francis Turbine Runner for Sand Laden Water

Krishna Prasad Shrestha, Bhola Thapa, Ole G. Dahlhaug, Hari Prasad Neupane, Nikhel Gurung and Atmaram Kayastha


Krishna Prasad Shrestha


Bhola Thapa


Ole G. Dahlhaug


Hari Prasad Neupane


Nikhel Gurung


Atmaram Kayastha

Abstract: Nepal has an enormous amount of water resources and the topography gives rise to a huge hydropower potential. Out of 83,000 MW, only about 43,000 MW is economically and technically feasible. However, rivers of Nepal contain heavy quantities of sand particles. This is why the hydropower plants of this region face severe sand erosion problem.

Erosion mechanism in hydropower is a complex phenomenon. It is a major technological challenge for R-O-R (Run off river) hydropower plants. There are several technologies to reduce erosion but none of them has proven to be economically viable. The hydraulic design of the turbine with a new design philosophy expected to reduce sand erosion considerably and this process is economic too.

This paper describes the alternative optimized design of Francis turbine runner for large sediment load. The process involves optimization to obtain specific Francis runner blade using not defined ANSYS CFX parametric study. The process also includes analysis of the runner blade using CFX parametric study and Fluid structure interaction simulation for specific blade design. Design and drafting of the runner and part model design for FSI (Fluid Structure Interaction) analysis have also been described.

Key words: Francis runner, optimization, CFD (Computational Fluid Dynamics), FSI

Introduction

Nepal possesess huge of hydropower potential but only a small amount of the total capacity is used. There are many socio economic challenges but the main technological challenge Nepal faces is the sediment erosion problem. Since most of the power plants are R-O-R type sediment erosion is more and has become a major problem. Almost all the rivers in the country contain sediments. The sediment content has more number of hard particles, which easily erode the turbine material and eventually reduces the efficiency and life of the power plant (B. Thapa, Sand Erosion in Hydraulic Machinery 2004). Sediment erosion in hydraulic machinery is a great challenge to overcome. Though several methods are there to overcome the problem, none of them has proved to be economically feasible. Therefore, there is a need of different methodology to tackle this problem.

Jhimruk hydropower plant is one of the most erosion affected power plant in Nepal. In monsoon, the flow is very heavy with high sediment concentration of hard abrasive particles esp. quartz. Due to this, damage in the turbine components are very high. With erosion, the thickness of the runner critically reduces and hence the reliability of the component decreases. From past experiences, it has been found that guide vanes, labyrinth seals and runner blades have greater amount of erosion. Chilime is one of the other power plants in which sediment erosion is very high. In the case of pelton turbine, erosion problem is mostly observed on nozzle, bucket and splitter (B. Thapa, Sand Erosion in Hydraulic Machinery 2004). The erosion does not only affect efficiency but also causes problems in operation and maintenance too.

To avoid sand erosion, Tungsten carbide coatings with Co, Ni, Cr, Mo as binders are widely used in turbine industry for erosion resistance. High Velocity Oxygen Fuel (HVOF) is used to spray such coatings. HVOF coating should be done maintaining uniform thickness of good adhesion to all points. However, in Francis this process is very difficult. Thus removal of coating from a weak spot will trigger the damage of HVOF coatings (Brekke 2008),(Thapa, Upadhyay, et al. 2005).

The other conventional method to avoid sediment erosion is by sediment management. Sediment management by construction of settling basins is a challenge in itself. Construction of such basins, maintenance and proper disposal of sediments makes it very costly and is not possible for all the hydropower plants due to geographical and tectonic conditions of Nepal (B. Thapa, Sand Erosion in Hydraulic Machinery 2004).

While Optimized design of Francis runner for large sand laden water incompasses a new design philosophy in the basic design. It has utilized ANSYS CFX parametric analysis and FSI simulation to develop less erosion impact hydraulic profile of the Francis turbine runner blade (Thapa, Shrestha, et al. 2011), (Shrestha, et al. 2012). The advent of the computer codes and the hardware, turbine design process and design engineers has made it more sophisticated and accurate than in past times (Drtina and Sallaberger 1999).

CFD and FSI analysis has added the values of design more accurately and meticulously. Two way FSI is more complicated in nature, so one way FSI has been performed in Fluid structure interaction simulation considering deformation in fluid itself (Aijun 2011).

For the CFD analysis three different turbulence models have been used. k-epsilon model is considered to be the industrial standard. In this model turbulence kinetic energy is defined as the variance of the fluctuation velocity. It is based on eddy viscosity concept (Souza, Moura and Junior 2003).

k-ω turbulence model is used for smooth shift from a low Reynolds number to a wall function formulation. For the CFD simulation a low Reynolds number grid is essential near wall grid resolution of at least y+ value greater than 2, (Souza, Moura and Junior 2003).

Recently, Shear Stress Transport (SST) model has also been developed. This model is more accurate than k-ω for treatment of total pressure in near wall flows (Flores, Bazin and Mazzouji 2008).

Jhimruk Power plant and Sand erosion problem

Jhimruk Hydroelectric Plant (JHP) is located in Pyuthan district of Nepal. Total installed capacity of JHP plant is 13.5 MW. There are three units of horizontally mounted Francis turbine. Each unit produces 4.5 MW of electric power (Shrestha, et al. 2012),(Gjosater 2011). During the design phase of JHP sediment load was not taken into consideration since sediment sampling was also not available.

Most of the sediment in JHP originates from the upper part of the catchment area and its tributaries (Pandit 2007). Sediment in this river contains mostly the quartz, feldspar, mica and other hard abrasive particles (B. Thapa, Sand Erosion in Hydraulic Machinery 2004). These suspended particles are responsible for the damage of the turbine component when entering in hydro turbine (B. Thapa, Sand Erosion in Hydraulic Machinery 2004),(Pandit 2007), (Bergmann-Paulsen, FSI-analysis of a Francis turbine 2012). Each year turbines in JHP faces heavy sediment erosion.

Development of the program "KHOJ"

Kathmandu University, Turbine Testing Lab (TTL) and Waterpower Lab of NTNU has jointly developed a MATLAB based High head Francis turbine design software called "KHOJ" for sediment erosion free turbines. It facilitates the development of preliminary design data for the Francis turbine design (Gjosater 2011),(Thapa, Eltvik, et al. 2012). Preliminary design data for the 3D design and computational domain have been generated by this software with reference to Jhimruk Power Plant of Nepal.

Objective

The main objective of this research is to design and develop a new Francis turbine runner that can handle sediment load. Some of the specific objectives are :

- To determine effective area and its impact on erosion on Francis turbine runner blade.
- To determine possible solution for the minimizing effect of sand erosion on turbine runner.
- To innovate optimization technology on Francis Turbine runner design.

Design Methodology of Francis Runner

Development of basic design data from the MATLAB Program "KHOJ"

The basic design data of Jhimrukh Power Plant in terms of head, discharge and efficiency are taken as the input parameters for the "KHOJ" Software. In this software there are different interfaces for the design of each component.

In the initial step in the design is the design of the runner blade. For the design of the runner blade, some of the parameters like outlet angle and acceleration of the water to the outlet are presumed. With the input parameters i.e. Head and discharge the runner design parameters is obtained i.e. inlet diameter, outlet diameter, inlet height. Within these constraints the profile of the runner blade is created. In this design runner blade profile is divided into 10 different sections with individual streamlines on the pressure and the suction side. After completion of the total length and the profile of the blade development, the hub and shroud for the runner blade are created. Similarly, the related parameters like labyrinth seals, position of guide vanes and stay vanes, number of guide vanes and stay vanes, thickness of the blade, number of sections of spiral casing are also extracted. Moreover, the hubs and shrouds for the guide vane and stay vane can also be extracted; which are also known as guide rings and stay rings. The thickness of the hub and shroud can be chosen which affects the position of the labyrinth seal in the hub and shroud of the runner. A file with all the required coordinates and the summary of the whole analysis performed is then exported and used. Throughout the study, CFD and FSI simulation were performed on Francis runner assembly having 888 mm inlet and 540 mm outlet diameter.

3D design in PRO/Engineer software

With the design extracted from the program "KHOJ", the 3D coordinates of the components are obtained. These coordinates are changed into compatible file format and imported to the Pro/ Engineer software.

To make the runner blades, initially the coordinates of the streamlines on the suction side and pressure side are imported. Then individual surfaces are created on each side of the blade. And all these surfaces are merged together and finally solidified.

The coordinates of the hub and shroud are also obtained for the runner with which hub and shroud for the runner is created. The labyrinth seals on the hub and shroud are also placed according to the position specified in the “Turbine data”. The number of labyrinth seals required is presumed and improvised with the repeated completion of CFD and FSI analysis.

Design of Cut Model for FSI analysis in PRO/ Engineer

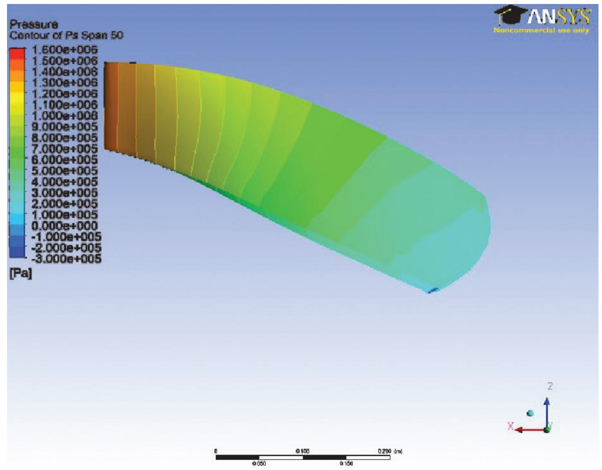
With the completion of the CAD model in Pro/Engineer, for the FSI analysis, the hub and shroud is divided equal to the number of blade. For the FSI analysis, hub and shroud is divided into 17 equal parts. In FSI, the analysis of a single blade is carried out and the same results are implied remaining identical parts and summarized of all results is viewed in ANSYS CFX.

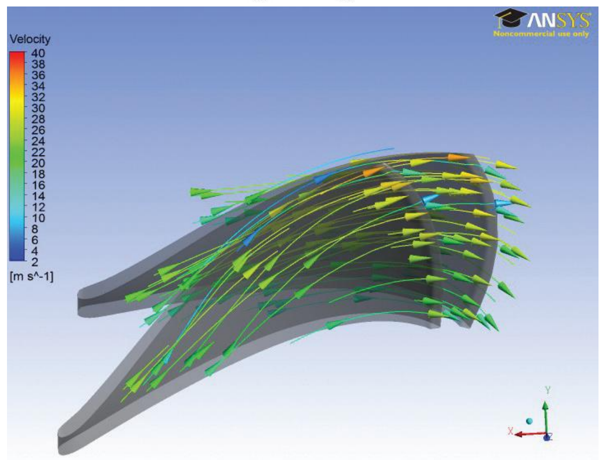
Francis runner has complicated profiles. To divide the runner into equal number of parts, the hub and shroud of the runner must be divided individually.

For dividing the hub, the top most pair of streamlines in the runner blade is selected and for the shroud, lower most pair of streamlines is selected. Using those streamlines a reference middle curve is created and is used to cut the profile into equal individual sections for an individual blade.

Design Optimization in ANSYS CFX

Optimization is done using ANSYS goal driven optimization facilities. Speed, flow rate and Velocity were kept constant during the process while the other parameters like head, efficiency etc. were determined by optimized process. The results are tabulated in table 1 below.





S.No.	P1-Velocity (V) (m/s)	P3-Head (H) (m)	P4-Shaft Power (W)	P5-Total Efficiency	P6- Flow (Q) (m3/s)	P7- Speed (N) (s^-1)
1	0.24	183.794	4084080	94.696	2.35706	104.72
2	0.2	218.972	4882860	93.4553	2.35706	104.72
3	0.28	160.439	3486090	93.0557	2.35706	104.72
4	0.22	199.2	4454800	94.5628	2.35706	104.72
5	0.26	171.097	3761720	94.0276	2.35706	104.72

Table 1. Optimized values for Velocity (V) head (H)

CFD Analysis

For CFD Analysis on five set of optimized the blades, data from Jhimruk power plant was considered as a reference. (Table 2)

S.No	Parameters	Value	Unit
1	Net design head(H)	201.5	M
2	Net discharge per unit(Q)	2.35	m^3/s
3	Runner efficiency(h)	96	%

Table 2. Data from Jhimruk Power Plant for Analysis

Erosion Study on Francis Runner Blades

Effect of erosion on blades has been studied on the five different sets of blades. The comparative studies have been carried out for the effect of erosion on blades and the velocity at turbine exit. The presented figure 1 to 5

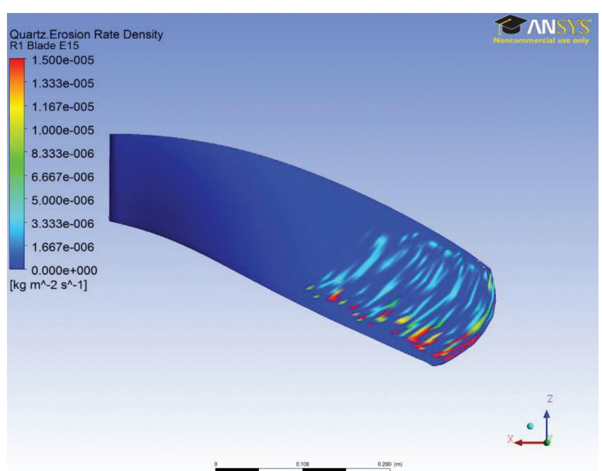


Figure1. Pressure and Velocity streamlines distribution and effect of sand erosion on R1 Blade

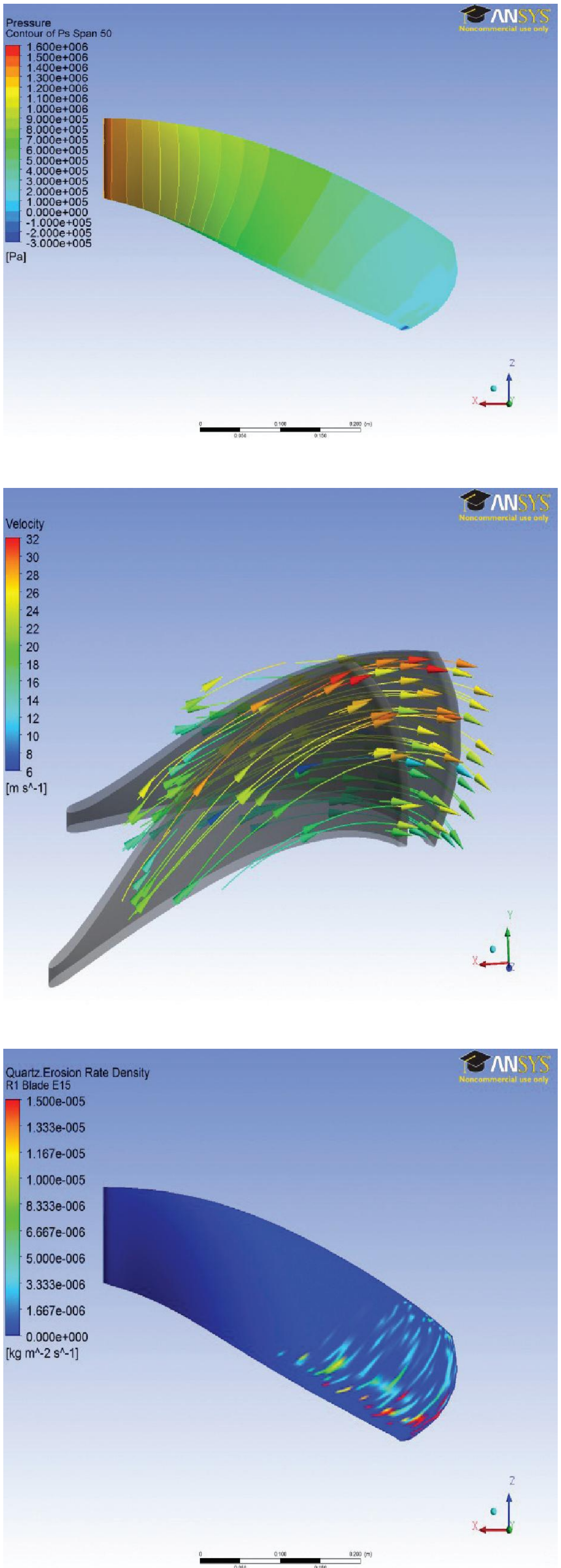


Figure 2. Pressure and Velocity streamlines distribution and effect of sand erosion on R2 Blade

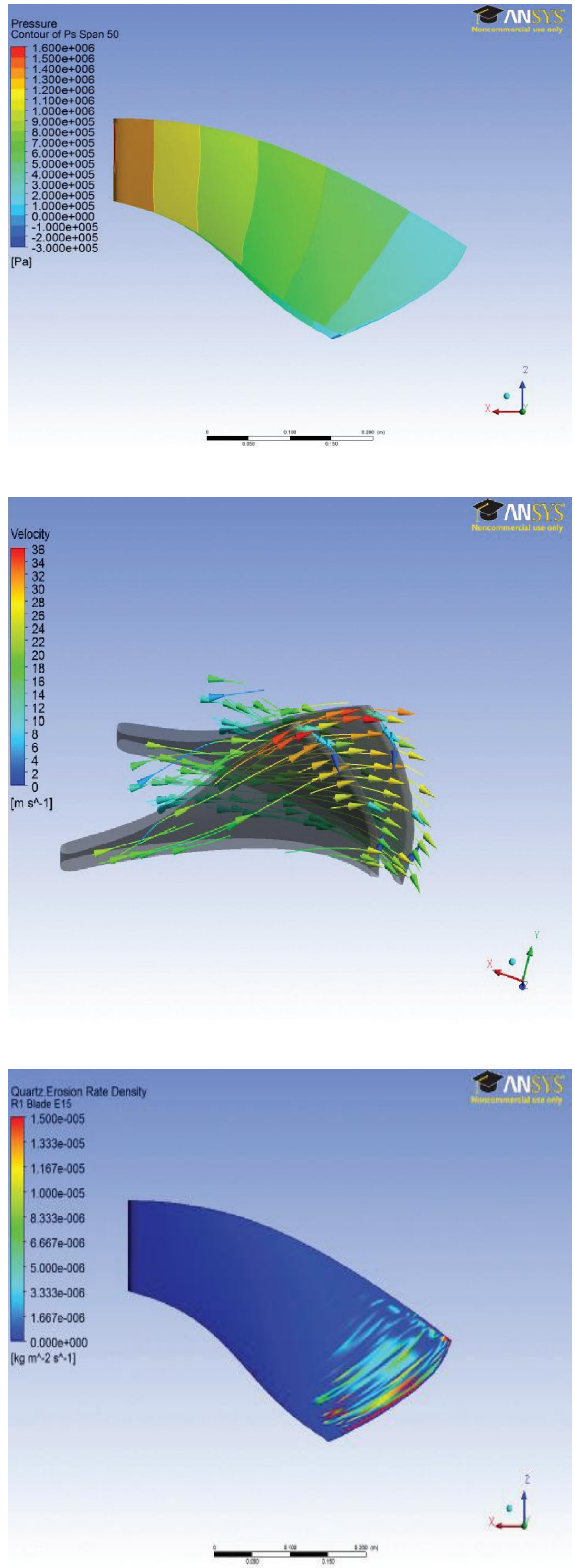


Figure 3. Pressure and Velocity streamlines distribution and effect of sand erosion on R3 Blade

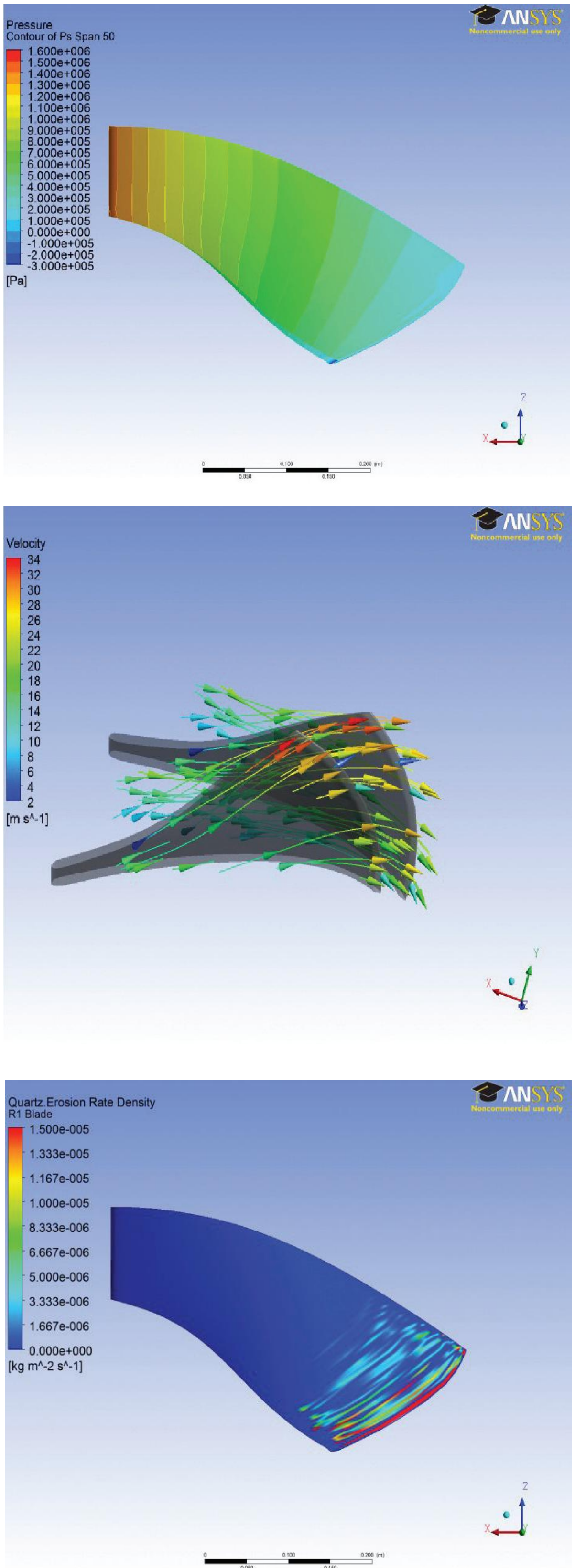


Figure 4. Pressure and Velocity streamlines distribution and effect of sand erosion on R4 Blade

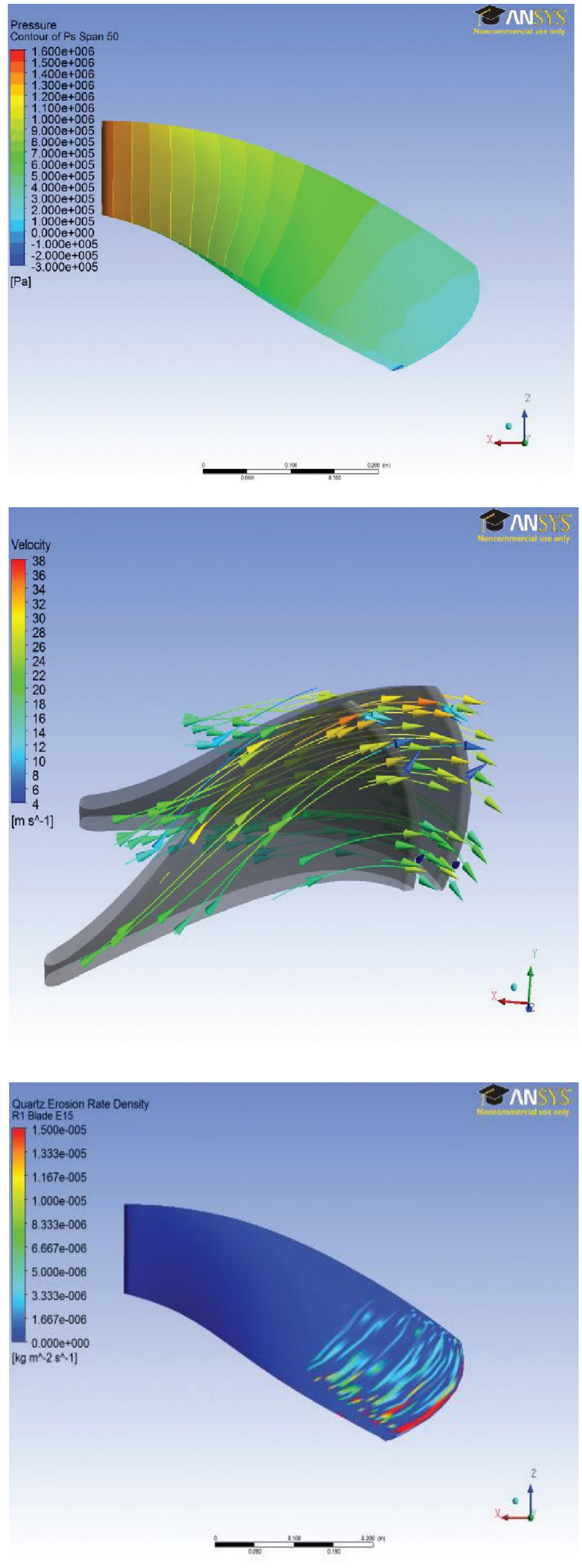


Figure 5. Pressure and Velocity streamlines distribution and effect of sand erosion on R5 Blade

shows the pressure distribution along the blades, velocity at outlet and effect of sand erosion on the blades.

Fluid Structure Interaction analysis On Francis Blade

Two different thicknesses of the blades were chosen for FSI analysis. Specification and operating condition of the blades are shown below. For FSI Analysis, Unidirectional coupling was chosen.

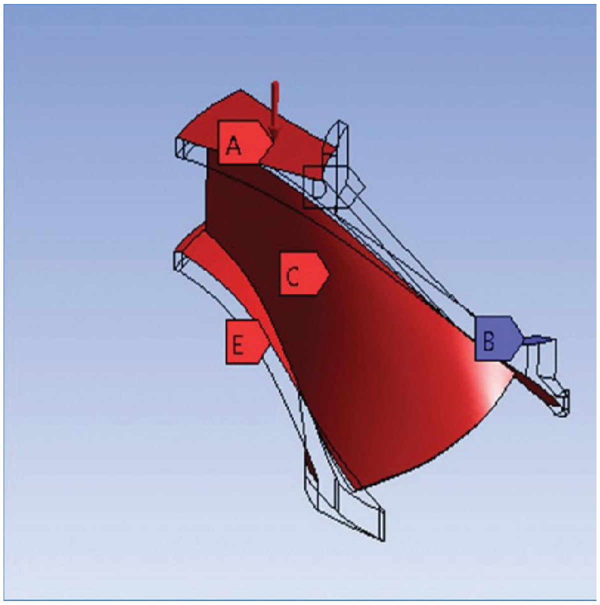


Figure 6. Location of applied boundary condition

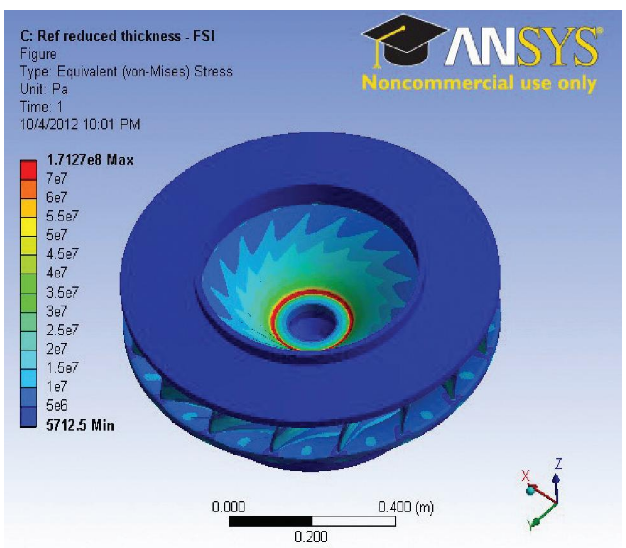


Figure 7. Equivalent stress distribution on runner assembly for R2

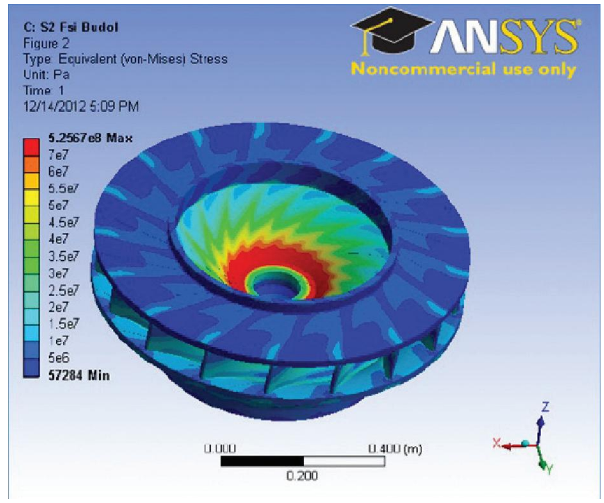


Figure 8. Equivalent stress distribution on runner assembly for R5

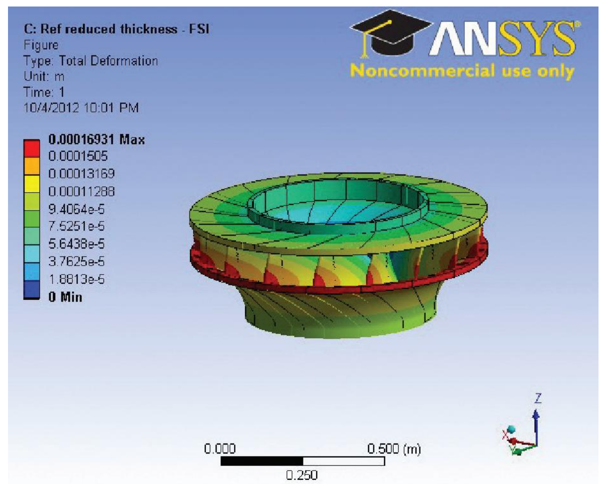


Figure 9. Total deformation on runner assembly for R2

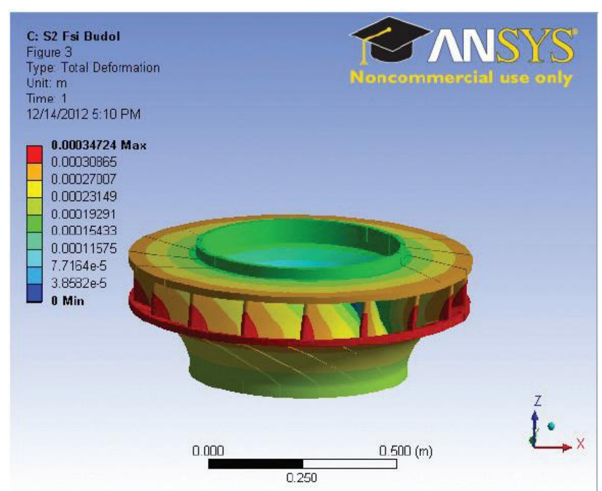


Figure 10. Total deformation on runner assembly for R5

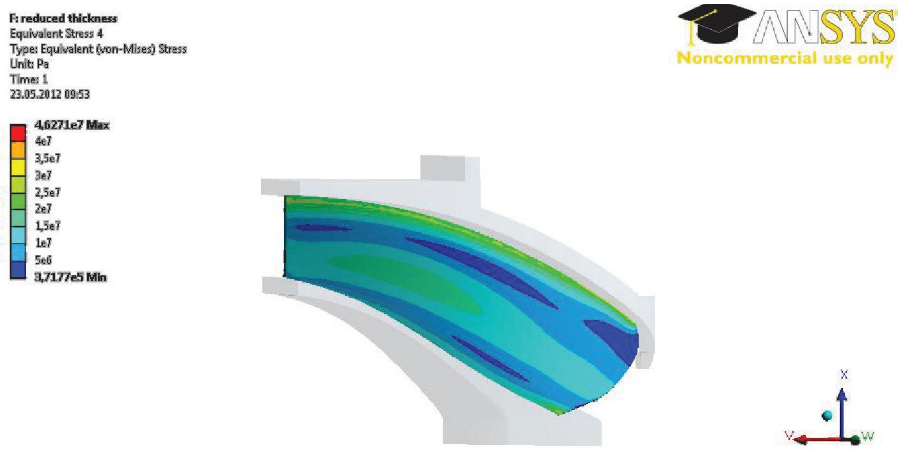


Figure 11. Equivalent von mesh stress on single blade for R2

Blade Shape	Thickness at leading/Trailing edge(mm)	Volume Flow rate (m3/s)	Condition of Operation
R2	15/8	2.35	Best efficiency point
R5	10/6	2.35	Best efficiency point

Table 3. Specification and operation condition

FSI Methodology

From the CFD results based on pressure distribution, velocity at trailing edge and surface plot of eroded blade and suction side of the blade, R2 and R5 blades can withstand erosion problem better than all other design. Hence, R2 and R5 blades were selected for the FSI analysis. Three-dimensional models were prepared in Pro/Engineer software by importing corresponding curves. Complete model was divided into seventeen equal parts and one of them was chosen for FSI analysis. Body sizing and match control meshing was performed in Design modular keeping triangular messing (Bergmann-Paulsen, Mechanical design of Francis turbine exposed to sediment erosion 2011). Boundary conditions were defined by variable load pressure, fixed support, imported pressure 1, imported pressure 2, and imported pressure 3 at different location in 3D model as shown in figure.

In Figure 6, A represents variable load pressure, B is the fixed support, C, D, and E represents imported pressure 1, 2, and 3 respectively.

FSI Simulation was performed in one of the sector of seventeen parts of the runner. Cyclic command was used to view and summarize the whole runner. Deformation due to pressure inside the Francis runner is shown in the figure.

Results and Discussion

Optimization methodology has been applied during curve generation process and CFD analysis. The outcomes of the CFD analysis Optimization results were found more useful to device the relationship between variables. The relationship between those variables significantly reduced the time of design and cost of the design (Aijun 2011), (Drtina and Sallaberger 1999). Particle tracking method was applied to identify the spot where it was more vulnerable to sand erosion (ANSYS 2012). Comparative study has been carried out based on pressure distribution, velocity at trailing edge and surface plot of eroded blade and suction side of the blade between the five set of optimized Francis runner blades. Results showed R2 and R5 blades can accommodate erosion problem among all other design. Hence, R2 and R5 blades were selected for the FSI analysis. Deformation due to pressure developed inside Francis Runner assembly has been determined by Fluid structure interaction simulation on R2 and R5 blade.

For the FSI analysis, unidirectional (one way coupling) was chosen for the both R2 and R5 blade. Deformation due to pressure was found to be 0.00016913m and 0.00030865m respectively which shows the design for the structural steel to be safe. From these results, it can be expected that Francis turbines runner design with design optimization can reduce sand erosion problem on runner blade.

Conclusion and Recommendation

It is found that R2 and R5 blade can withstand sand erosion problem than traditional design of Francis turbine runner. Optimized design of Francis turbine runner can reduce sand erosion by 20% to 25% without much losing its efficiency. The blade thickness taken for fluid structure interaction simulation from leading edge to trailing edge changed from 10mm to 6mm. The results showed the thickness to be safe. The present values and data are obtained by 3D design in Pro/ Engineer, simulation on MATLAB, and ANSYS 14. However model tests in the laboratory with real life conditions are essential for the verification of those results obtained from computer simulations.

- -

Acknowledgement

I would like to acknowledge and extend my heartfelt gratitude to my supervisors Dr. Bhola Thapa and Dr. Ole Gunnar Dahlhaug who have helped to conduct my research. I would also like to thank Mette, Jonas and Peter for their continuous support during project work at NTNU- KP Shrestha.

Krishna Prasad Shrestha*, M.E. Mechanical Engineering is a PhD candidate at the Department of Mechanical Engineering of His current research is based on Design of Francis Turbine for large sediment load. He is also an active member of Turbine Testing Lab, Kathmandu University (KU) Nepal.*
Corresponding address: kp@ku.edu.np

Bhola Thapa*, PhD is a Registrar and the Professor in the Department of Mechanical Engineering, Kathmandu University Nepal.*
Corresponding address: bhola@ku.edu.np

Ole G. Dahlhaug*, Phd is a Professor in Department of Energy and Process Engineering, Norwegian University of Science and Technology, Norway. He has been actively conducting research on sediment erosion of turbine components and efficiency measurement of hydropower plants.*
Corresponding address:ole.g.dahlhaug@ntnu.no

Hari Prasad Neupane, *PhD is an Associate Professor in the Department of Mechanical Engineering, Kathmandu University Nepal.*
Corresponding address: hari@ku.edu.np

Nikhel Gurung, *BE Mechanical Engineering is currently working as a researcher in Turbine Testing Laboratory, Kathmandu University. His current research is based on Prospects of Utilization of Reversible Pump Turbines in Nepalese Power Plants.*
Corresponding address: nikhel.gurung@ku.edu.np

Aatma Ram Kayastha, *BE Mechanical Engineering is currently working as a researcher in Turbine Testing Laboratory, Kathmandu University. His current research is based on Feasibility study of Turbine Manufacturing in Nepal.*
Corresponding address: aatmakayastha@gmail.com

References

Aijun, Sun, 2011, Numerical simulation of Fluid – Structure Interaction for blade abased on CFX and Workbench, 2nd International Conference on Control, Instrumentation and Automation(ICCA).

ANSYS,2012, ANSYS help Version 14.

Bergmann-Paulsen, Jonas, 2012, FSI-analysis of a Francis turbine, Masters Thesis, Trondheim: NTNU.

Bergmann-Paulsen, Jonas, 2011, Mechanical design of Francis turbine exposed to sediment erosion, Project Thesis, Trondheim: NTNU.

Brekke, H., 2008, Konstruksjon av Pumper og turbine. Notes, Waterpower laboratory NTNU.

Drtina, P., and M. Sallaberger, 1999, Hydraulic turbines- basic Principles and start-of art computational fluid dynamics applications, ProcInstnMechEngrs Vol213 part.

Flores, Emmanuel., Daniele. Bazin, and Farid. Mazzouji, 2008, Francis Turbine Operating at Low Head : FOZ Do Chapeco Case Study, 24th Symposium on Hydraulic Machinery and Systems, FOZ DO IGAUSSU.

Gjosater, K., 2011, Hydraulic design of Francis Turbine Exposed to Sediment Erosion, Masters Thesis, Trondheim: NTNU.

Pandit, H.P., 2007, Hydrocyclones: Alternative Devices for Sediment Handling in R.O-R Projects,International Conference on Small Hydropower-Hydro Srilanka. Srilanka.

Shrestha, K.P., B. Thapa, O.G. Dahlhaug, Hari P. Neopane, and B.S. Thapa, 2012, Innovative Design of Francis Turbine for Sediment Laden Water, International Conference on Technology & Innovative Management, Kathmandu.

Souza, Luis C. Ecardo Oliveria de, Marcelo dias de Moura, and Antonino C. P. Brasil Junior, 2003, Assessment of Turbulence Modelling for CFD Simulations into hydro turbine spiral Casing, Brazil: 17th International Mechanical Engineering Congress (COBEM 2003) at São Paulo (Brazil).

Thapa, B.S., K.P. Shrestha, B. Thapa, and O.G. Dahlhaug, 2011, Experiences of R&D of Hydraulic Turbines at Kathmandu University, First Asia-Pascific Forum on Renewable Energy, Busan.

Thapa, B.S., M. Eltvik, K. Gjoasater, O.G. Dahlhaug, and B. Thapa. 2012, Design Optimization of Francis Runner for Sediment Handling, Hydropower and Dams, Chang Mai, Thailand.

Thapa, B, 2004, Sand Erosion in Hydraulic Machinery, PhD Thesis, NTNU.

Thapa, Bhola, P Upadhyay, O.G. Dahlhaug, M. Timsina, and R. Basnet, 2005, HVOF coatings for erosion resistance of hydraulic turbines: Experience of Kaligandaki-A Hydropower Plant, Water Rseources and Renewable Energy development in Asia.