Design analysis of Mixed Flow Pump Impeller Blades Using ANSYS and Prediction of its Parameters using Artificial Neural Network

Sambhrant Srivastava, Apurba Kumar Roy and Kaushik Kumar

Abstract

Mixed flow pumps are extensively used in large thermal power plants for cooling water duties. However, design of mixed flow pump impeller and its blades seems to be a fairly complicated operation even to the person having thorough technical knowledge in the field of turbomachinery. The main aspect of designing an impeller blade for a mixed flow pump impeller is the root section which encounters the maximum stress. Here in this paper mixed flow pump impeller blades are designed having two different blade positioning in the meridional annulus. The stress development in the pump blades are evaluated using FEM analysis. Artificial neural network (ANN) is used to optimize the thickness of the aero foil blade cross-section with respect to Von-misses stress. It is observed that the mixed flow pump impeller blade with inlet inclined blade position in the meridional annulus is more suitable with respect trapezoidal blade as predicted through ANN using RAPID MINER 5.3 software. This is because of the fact that the mean square error for inlet inclined position is much less than that for the trapezoidal blade.

Keywords: Optimization, Mixed flow pump impeller, Design, ANSYS, RAPID MINER, Artificial neural network

1. Introduction

The mixed flow pumps are generally being used in large thermal power plants for cooling water duties. The mixed flow pump is a unification of radial & axial characteristics. The design of mixed flow impellers of high specific speed is a direct extension of the well-established empirical methods of the designing of radial flow impellers. The extension of similar methods serves for the design of mixed flow impellers, but the introduction of near diagonal flow layout at a still larger specific speed stimulated the incorporation of axial pump impeller design techniques in mixed flow pump technology.

* Corresponding author: +91-9431-597463
E-mail: ksrinivasan.cad@gmail.com
The design procedure for mixed flow impellers are not as well established as those for axial d centrifugal machines. Axial flow pump impellers lend themselves to design methods based on flow in aero foil cascades while the design of centrifugal pump impellers tend to depend on a large number of empirical correlation. Mixed flow impellers of large specific speed have conical flow paths with balding fairly similar to that of axial flow pump impellers. The industrial design practice of mixed flow pump impeller design starts with the estimation of approximate meridional streamlines by dividing the annulus by the equal area method [Hao et al. (2013)]. Empirical co-efficient depending on the specific speed used to fix the inlet and outlet blade angles. Similar co-efficients are used to determine overall impeller layout before the meridional streamlines are estimated. The inlet and outlet angles being fixed in this manner, the blade sections are laid out on the developed stream surfaces. The above industrial method is basically based on some empirical co-relations and design constants.

The industrial design method often ignores the actual happening within the pump flow passage and is consequently a poor guide when the question of a new design and development of pumps comes to picture. In the above design process the designer has less control than desirable over events. The lack of clear cut rational basis also inhibits the correction of manufacturing of shortfalls in expected performance. To overcome the above difficulties, one has to formulate a rational basis for the designing of impellers starting from basic principles, such that the use of empirical co-relations is minimized. Such a design from the basic principles has advantages that the designer will have more control over the outcome of his design, while keeping the physical principle constantly in view and enables him to rectify any faults in the performance of the pump.

**Nomenclature**

| Symbol | Description                             | Unit |
|--------|-----------------------------------------|------|
| C      | Blade chord length, mm                  | mm   |
| D      | blade diameter, mm                      | mm   |
| g      | acceleration due to gravity, m/sec²     |       |
| H      | pressure head, m                        |       |
| l      | blade span, mm                          | mm   |
| N      | rotational speed, rev. / min.           |       |
| NS     | specific speed rev./sec.                |       |
| P      | power, kW                               | kW   |
| Q      | volumetric discharge, m³/min.           |      |
| r      | radius, mm                              | mm   |
| S      | blade spacing, mm                       | mm   |
| ω      | angular velocity, rad. /sec             |       |
| λ      | blade stagger angle, degree             | degree |
| α      | blade angle, degree                     | degree |
| σ      | Von Mises stress, MPa                   | MPa  |
| σB     | bending stress, MPa                     | MPa  |
| τ      | shear stress, MPa                       | MPa  |

The research and development on mixed flow pump have not gone to an extent as compared to conventional centrifugal and axial flow pumps. The flow through the mixed flow pump is quite complex. The design of the mixed flow pump impeller is much complex because of its complex geometry and large number of flow variables play a very important role in its optimum design.

Over a period of time research on mixed flow pump has been carried out by various researchers. Wislicenus (1965) initiated the design of a mixed flow pump impeller. The modification of mixed flow pump impeller was carried out by Myles (1965). Busemann (1928) developed a formula for slip velocity for a mixed flow pump. Senoo and Nakase (1972), Inoue et al. (1980) developed a design method by calculating the meridional stream line. Stepanoff (1967) gave a design procedure for mixed flow pump impeller. Neumann’s (1991), Gahlot and Nyiri (1993) have suggested the step-by-step design procedure for designing Mixed flow pumps. Takayama and Watanabe (2009) presented a multi-objective optimization strategy of mixed-flow pump design by means of Three Dimensional Inverse Design Approach. Kim & Kim (2011) developed an optimization procedure for high efficiency design of mixed-flow pumps. Hao et al. (2013), Mehta and Patel (2013) studied the effects of meridional flow passage shape on hydraulic performance of mixed-flow pump impellers. Sunder (1981) presented a three-dimensional method of stress analysis using finite element techniques for determining the stress distribution in centrifugal impellers. Ramamurti and Balasubramanian (1987), Jonker and Van Essen (1997), Lemeš and Zaimović-Uzunović (2002), Bhope and Padole...
(2003), Arewar and Bhope (2013) contributed much on the stress analysis for highly complex blades of various turbomachines. Sambhrant Srivastava et al. / Procedia Engineering 97 (2014) 2022 – 2031

Samanta (2008) used ANN technique to validate the result of CNC machining. Karnik (2008) analyzed high speed drilling process by developing an artificial neural network (ANN) model with spindle speed, feed rate and point angle as the affecting parameters. Tosun (2001) estimated tool life using ANN with back propagation (BP) algorithm. Somashekhar (2010) used trained artificial neural network model for estimating the MRR and is improved using optimized machining parameters. Panda (2007) trained feed forward artificial neural network based on the Levenberg-Marquardt back propagation technique of appropriate architecture of the logistic sigmoid activation function to predict the material removal rate. Although, a number of excellent literatures are available on the flow analysis through mixed flow pumps, but study on design and optimization of mixed flow pump impeller blades using stress analysis and Artificial neural network are scanty. In the present work, design of mixed flow pump impeller blades were carried out for two different blade positioning in the meridional annulus based on basic principles of fluid mechanics and turbo machinery as shown in Fig.1. The blades were compared on basis of stress analysis and optimization of the blade thickness was carried out using artificial neural network.

2. Design methodology

In this work the designs of the mixed flow pump impeller blades are based on free vortex theory. The stream surfaces through the meridional annulus are kept parallel to hub and casing, whereas, the hub and casing are parallel to one another. It is also assumes that the meridional velocity distribution remains uniform across the annulus. In the present case a mixed flow pump impeller has been designed for discharge (Q) =0.125 m³/sec., head developed (H) = 5 m, speed of rotation (N) = 1000 rev/min. The fundamental relations were developed based on principles of fluid mechanics and turbo-machinery and the design and development was carried out for two different blade positioning, inlet inclined(case-I) and trapezoidal(case-II) on the meridional annulus as mentioned earlier.

2.1 Modeling of pump impeller blades

Once the design parameters such as blade angles, blade stagger angle, blade chord length, blade solidity are known, the development of complex shaped blades have been were carried out by superimposing the various blade sections one over another to satisfy blade stagger angle on the conical surface of the pump impeller. To calculate the span-wise variation of the blade angles, the blade span has been divided into ten equal sections parallel to hub and casing. The span-wise variation of blade angles at inlet and outlet and blade stagger angle for inlet inclined and trapezoidal blade positioning in the meridional annulus are shown in Fig. 3 and 4 respectively.
Then 3D model of the two types of the impeller blades are developed using CATIA modeling software. Here in this pump impeller NACA 10C4 blade profile is used.
2.2 Stress analysis of the impeller blades

The calculation of stresses in a mixed flow pump impeller blade is extremely complicated owing to number of reasons: the complex loading characteristics and the geometry of the blade is rather complicated. To get an accurate estimation of the stresses in the blades, validation of stress values are required to be compared with the calculated values. To accomplish the above a simplified method of stress validation among the calculated and numerically predicted values was carried out by replacing the twisted blades with an equivalent plate having rectangular cross-section, which acts like a cantilever. The material properties and the volume of both plate and blade were kept identical. The theoretical calculation of Von Mises stress was carried out using the equations. (1-6). It is assumed that each blade of the mixed flow pump impeller acts as a cantilever fixed to the hub and due to torque applied on the impeller; a surface force acts on the blade.

Torque applied on the plate:

\[ T = \frac{w \cdot l \cdot b \cdot s}{2} \]  

Also, torque applied:

\[ T = \frac{(P \cdot (60) \cdot 1000)}{(2 \cdot \pi \cdot N)} \]  

Where,

\[ P = 20 \text{ Kw}, \quad N = 1000 \text{ rev./min.}, \quad n = \text{number of blades in the impeller} = 8 \]
\[ L = \text{span of each plate} = 58 \text{ mm}, \quad b = \text{mean width of each plate} = 162 \text{ mm}, \quad t = \text{thickness of each plate} = 17 \text{ mm} \]

So from the above equation,

\[ w = \frac{2T}{b \cdot s} = \frac{2 \cdot (191000)}{58^2 \cdot (162) \cdot 8} = 0.088 \text{ N/mm}^2 \]  

Bending stress is given by the relation:

\[ \sigma_b = \frac{M}{l} \]  

where,

M=bending moment=w. b N-m, l=moment of inertia= (b. t^3)/12 m^4, y=varrying distance from neural axis, m.

and shear stress can be written as:

\[ \tau = \frac{6w \cdot b \cdot l}{b \cdot t^3} \cdot \frac{(t^2)}{(4-y^2)} \]  

So, Von Mises stress is given by the relation:

\[ \sigma_b = \sqrt{\sigma^2 + 3\tau^2} \]
So, the calculated value of the Von Misses stress at the root of the plate is $3.07299 \times 10^6$ N/m$^2$.

While calculating the Von Misses stress the following material properties are taken into consideration.

Material: Bronze

- Young Modulus: $1.1 \times 10^5$ MPa
- Poisson Ratio: 0.341
- Density: $8.86 \times 10^{-9}$ kg/mm$^3$
- Thermal Expansion: $1.78 \times 10^{-5}/^\circ$K
- Yield Strength: $5.2 \times 10^8$ N/m$^2$

Once the value of the Von Misses stress has been calculated for the plate, FEM convergence test is carried in the plate with different size of the element find out the optimum size of the element using ANSYS. Using the optimum element size, numerical stress analysis for the pump impeller blades has been carried out. The Von Misses stresses were calculated considering the material properties of Bronze. Fig. 10 shows the analysis to find out the optimal element size for FEM analysis. From Fig.10 it is observed that the optimal size of the element is 4.25 mm. Here, tetrahedral element is used for the present analysis. Span wise variation of Von Misses stress for the plate for an element size of 4.25 mm is shown in Fig.11.

As the mixed flow pump impeller blades have complex surfaces, before applying any force to the impeller blades, calculations are carried out for the surface force density to be applied in the blades for stress analysis. For the case of inlet inclined blades (case-I) the surface area of each side of the blade is found to be 0.014 m$^2$ therefore, so a surface force density of $58805$ N/m$^2$ is applied to the impeller blade for case-I. For trapezoidal blade positioning (case-II) the surface area of each side of the blade is found to be 0.013 m$^2$ so a surface force density of $63328$ N/m$^2$ is applied to blades for case-II.

3. Results and discussion

Using the optimum element size, numerical analysis for Von Misses stress on the pump impeller blades has been carried. The span wise variation of Von Misses stress for case-I and II are shown in Figs. 12-13 respectively, whereas the span wise variation of Principal stress for case-I and II are shown in Figs. 14-15 respectively.
From the Fig. 12 and Fig. 13 it is observed that the Von Misses stress at the root of the pump blade for inlet inclined blade position is 12.131 MPa, whereas for trapezoidal blade positioning in the meridional annulus it is 24.322 MPa. While comparing the maximum principal stresses, from Fig. 14 and Fig. 15 it is observed that the maximum value of principal stress for inlet inclined blade positioning is 20.751 MPa and for trapezoidal blade positioning it is observed to be 16.751 MPa at the root of the blade.

The effectiveness of the design of the blade profile and the positioning depends on the stresses developed at the root of the blades. From the design analysis it is observed that the Von Misses stress at the root of the pump blade for inlet inclined blade position was much lower than that for trapezoidal blade positioning in the meridional annulus which indicates that the inlet inclined blade position is a better option than the other one for the application.

### 3.1 Artificial neural network validation

In both the cases (I-II) blades are like cantilever beam and there maximum von-misses stress are at the fixed end of aerofoil cross-section, taking 25 nodes value of stress varying with their thickness and training in RAPID MINER 5.3 and calculating the mean square error with 2 hidden layer 2-4 nodes respectively with the calculated von-misses stresses.

\[
\text{MSE} = \frac{1}{n} \sum_{i=1}^{n} (\hat{Y}_i - Y_i)^2.
\]  
(7)

If \( \{\hat{Y}\} \) is a vector of \( n \) predictions, and \( Y \) is the vector of the true values.
Fig. 16. Artificial neural network diagram with 2 hidden layers.

Table 1: Estimation of mean square error of thickness for case-I.

| Node NO. | Von-misses stress (MPa) | Thickness (mm) | Predicted thickness (mm) | Mean square Error % |
|----------|-------------------------|----------------|--------------------------|---------------------|
| 1        | 12.138                  | 0              | 10.68732358              | 277.3894353        |
| 2        | 5.1323                  | 1.395          | 4.503840654              | 169.2607878        |
| 3        | 3.3975                  | 1.72           | 3.030538129              | 143.9932604        |
| 4        | 2.0427                  | 2.765          | 2.943200557              | 93.45622776        |
| 5        | 1.9386                  | 3.53           | 2.941212035              | 62.43876065        |
| 6        | 2.5211                  | 4.797          | 2.957181363              | 33.31219773        |
| 7        | 5.3412                  | 6.463          | 5.006753492              | 8.963948679        |
| 8        | 5.9452                  | 6.781          | 6.774548623              | 8.690951909        |
| 9        | 6.8917                  | 7.7            | 9.116834042              | 2.818093978        |
| 10       | 8.0137                  | 7.18           | 10.27919052              | 3.957597903        |
| 11       | 8.8443                  | 7.052          | 10.54671447              | 15.98238612        |
| 12       | 9.9153                  | 7.875          | 10.65356931              | 8.439594981        |
| 13       | 9.5582                  | 9.572          | 10.63254362              | 0.00976236         |
| 14       | 9.9481                  | 10.506         | 10.65505763              | 6.863345931        |
| 15       | 9.8773                  | 11.057         | 10.65176425              | 20.92337316        |
| 16       | 10.484                  | 11.507         | 10.67222561              | 23.51348468        |
| 17       | 10.485                  | 10.506         | 10.67224779              | 4.860073703        |
| 18       | 10.066                  | 11.994         | 10.65991508              | 36.41322674        |
| 19       | 10.189                  | 12.233         | 10.66425166              | 54.24514749        |
| 20       | 10.272                  | 12.651         | 10.66681112              | 81.97981695        |
| 21       | 10.173                  | 12.76          | 10.66372585              | 102.52809          |
| 22       | 9.3354                  | 12.547         | 10.61358647              | 111.3597644        |
| 23       | 8.5445                  | 12.1755        | 10.47994641              | 113.6100286        |
| 24       | 6.6713                  | 8.847          | 8.692321966              | 23.42749959        |
| 25       | 3.3419                  | 0              | 3.022349752              | 147.8271285        |
Table 2: Estimation of mean square error of thickness for case-II.

| Node NO. | Von-misses stress (MPa) | Thickness (mm) | Predicted thickness (mm) | Mean square Error % |
|----------|-------------------------|-----------------|--------------------------|--------------------|
| 1        | 23.257                  | 0               | -1.63180617662512        | 977.3001392        |
| 2        | 7.2213                  | 1.337           | 6.77801409678007         | 817.2623088        |
| 3        | 3.213                   | 2.791           | 6.79708814928633         | 659.452128         |
| 4        | 2.0573                  | 3.546           | 6.798844394100614        | 584.179232         |
| 5        | 1.9057                  | 4.277           | 6.799021867312165        | 515.6441808        |
| 6        | 2.182                   | 5.103           | 6.798690430341275        | 443.3467136        |
| 7        | 2.7823                  | 5.827           | 6.79783611110084         | 384.4658208        |
| 8        | 3.3872                  | 6.5149          | 6.7967493471017          | 332.405824         |
| 9        | 4.2571                  | 7.132           | 6.79463968975543         | 288.9252048        |
| 10       | 4.0175                  | 7.5667          | 6.795310344011844        | 260.1252866        |
| 11       | 6.3007                  | 8.1083          | 6.785815744635403        | 226.358043         |
| 12       | 7.4087                  | 8.5309          | 6.777027845278477        | 201.64             |
| 13       | 8.7812                  | 9.3956          | 6.7589475945769655       | 155.5158644        |
| 14       | 7.7642                  | 9.6257          | 6.773270526016932        | 144.2497082        |
| 15       | 6.9358                  | 9.7825          | 6.781258871121159        | 136.8151302        |
| 16       | 6.1315                  | 9.8856          | 6.786847659766686        | 132.0338884        |
| 17       | 6.1358                  | 9.9811          | 6.786822283239155        | 127.6809602        |
| 18       | 5.7113                  | 9.9153          | 6.78913092826259         | 130.6723334        |
| 19       | 5.0342                  | 9.8342          | 6.792099020389958        | 134.4069236        |
| 20       | 4.5621                  | 9.6526          | 6.793748881089449        | 142.9602836        |
| 21       | 4.5743                  | 9.09609         | 6.79370964731518         | 170.8149669        |
| 22       | 3.3498                  | 8.1737          | 6.796824173272264        | 222.4393274        |
| 23       | 2.5792                  | 7.9438          | 6.798147579259598        | 236.3600256        |
| 24       | 2.0482                  | 4.6218          | 6.798855342366476        | 484.8011312        |
| 25       | 4.2348                  | 0               | 6.794726704651225        | 977.3001392        |

To predict the thickness of the blades using ANN relative to von-misses stress. Predicted thickness value and true value is compared against both the cases (I & II). results are shown below in Fig.16 and Fig.17.

Fig.17. Predicted thickness variation (I) with respect to von-misses stress

Fig.18. Predicted thickness variation (II) with respect to von-misses stress.
As shown in above figures it can be clearly seen that, for minimum Von-misses stress, the critical thickness of case (II) is 6.7mm, whereas for case (I) is 2.5mm. This estimated result indicates that for trapezoidal blade thickness needs much improvement than that for the inlet inclined blade as depicted in Table 1 and Table2. These data confirms the suitability of inlet inclined blade thickness over trapezoidal blade thickness with reference to the respective von-misses stress across the span.

5. Conclusion
The effectiveness of the design of the blade profile and the positioning depends on the stresses developed at the root of the blades. From the design analysis it is observed that the Von Misses stress at the root of the pump blade for inlet inclined blade position was much lower than that for trapezoidal blade positioning in the meridional annulus which indicates that the inlet inclined blade position is a better option than the other one for the application. The observation was supported by the artificial neural network analysis done using RAPID MINER 5.3 where the estimated mean square error was less in case of inlet inclined blade position than that for trapezoidal blade positioning in the meridional annulus. This also indicated that the improvement required in the inlet inclined blade position would be less than that for trapezoidal blade positioning.

6. References
[1]Arewar, A. P. and Bhope D. V., 2013, Stress analysis of axial flow fan impeller, International Journal of Engineering Research and Applications (IJERA), Vol.3, issue 1, pp-2086-2090.
[2]Bhope D.V. and Padole P.M., Experimental and theoretical analysis of stresses, noise and flow in centrifugal fan impeller, Mechanism and Machine Theory, 2004, Volume 39, Issue 12, pp.1257-1271.
[3]Bing, H. C., Shuliang, T. L. and Zhu, B., Effects of meridional flow passage shape on hydraulic performance of mixed-flow pump impellers. Chinese Journal of Mechanical Engineering, 2013, Volume 26, Issue 3, pp.469-475.
[4]Busemann, A., The pump head ratio of radial centrifugal pumps with logarithmic spiral blades (In German), Z. Angew. Math. Mech. March 1928, 8 (5), pp.372-384.
[5]Gahlot V.K. and Nyiri A., Impeller Pumps, Theory and Design, 1993, M.A.C.T., Bhopal.
[6]Inoue, M., Ikui, T., Kamada, Y. and Tashidaro, M., A quasi three dimensional design of diagonal flow impellers by use of cascade data. IAHR, 10th Symposium, Tokyo, 1980, pp. 403-414.
[7]Jim-Hyuk Kim and Kwang-Yong Kim, Optimization of Vane Diffuser in a Mixed-Flow Pump for High Efficiency Design. International Journal of Fluid Machinery and Systems Vol. 4, No. 1, January-March 2011.
[8]Jonker, J. B. and Van Essen, T. G., A finite element perturbation method for computing fluid-induced forces on a centrifugal impeller, rotating and whirling in a volute casing, International Journal for Numerical Methods in Engineering, 1997, Vol. 40, pp. 269-294.
[9]Karnik.S.R, Delamination analysis in high speed drilling of carbon fiber reinforced plastics (CFRP) using artificial neural network model, 2008 Elsevier Ltd.
[10]Mehta, M.P. and Patel, P.M., Performance analysis and optimization of mixed flow pump. International Journal of Emerging Trends in Engineering and Development, 2013, Issue 3, Vol.1, pp 647 – 661.
[11]Myles, D.J., A design method for mixed flow fans and pumps, Report No. 117, National Engg. Laboratory, 1965.
[12]Neumann, B., The interaction Between Geometry and Performance of a centrifugal Pump, 1991, Mechanical Engineering Publications, London.
[13]Panda ,D.K., Artificial neural network Prediction of Material Removal Rate in Electro Discharge Machining, Materials and Manufacturing Processes, 20: 645–672, 2005Ramamurti, V. and Balasubramanian, P., Steady state stress analysis of centrifugal fan impellers, Computers & Structures, 1987, 25 (1), pp. 129-135.
[14]Samanta.B, Surface roughness prediction in machining using soft computing, International Journal of Computer Integrated Manufacturing 2008.
[15]Samar Lemeš and Nermina Zaimović-Uzunović, Mode shapes of centrifugal pump impeller, 6th International Research/Expert Conference on Trends in the Development of Machinery and Associated Technology, TMT 2002, Neum, B&H, 18-22 September, 2002.
[16]Senoo, Y. and Nakase, Y., An analysis of flow Power, 1972, Paper No. 71-GT-2, pp43-72.Sham Sunder, K, Finite Element Analysis of Centrifugal Impellers, Ph.D. Thesis, School of Mechanical Engineering, Cranfield Institute of Technology, 1981.
[17]Somashekar K. P., Optimization of Material Removal Rate in Micro-EDM Using Artificial neural network and Genetic Algorithms, Materials and Manufacturing Processes, 25: 467–475, 2010.
[18]Stepanoff, A.J., Centrifugal and Axial flow pumps, 1957, John Wiley and sons 2nd Edition, New York.
[19]Tosun N., A study of tool life in hot machining using artificial neural networks and regression analysis method, 2002 Elsevier Science B.V.
[20]Wislicenus, G. F., The Design of mixed flow pumps. Proceedings of the symposium held at the N.E.L.Glasgow, 1965.
[21]Yumiko Takayama and Hiroyoshi Watanabe, Multi-Objective Design Optimization of a Mixed flow impeller. ASME 2009, Fluids Engineering Division, Summer Meeting. Colorado USA.