Modal Analysis of Francis Turbine Blade Using Composite Material

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ABSTRACT

Performance of rotating equipment majorly depends upon mass of rotating components & vibration occurring in them while in operation. Major rotating mass is in runner which tends to generate more vibration in the system. Thereby reducing weight of runner will not only reduce the vibration but also increase the overall efficiency. To reduce the weight we should concentrate on alternative material such as composites. Peak amplitude and damping behaviour is proven better in composite materials rather than in steels. In this paper we have conducted modal analysis through Ansys & further the natural frequency results for Francis Turbine blade of stainless steel & glass fibre are compared.

Keywords-Francis, Modal Analysis, Frequency, Glass Fibre, Composite

1. INTRODUCTION

The basic idea is to study the vibration response & weight optimization that can be achieved using glass fibre as alternative material to stainless steel. Low density of Glass Fibre can significantly reduce the weight of turbine blade. Modal analysis performed on Francis Turbine blade made of stainless steel. First six mode shapes & corresponding natural frequencies are determined. For the blade of same dimensions the material is changed to glass fibre and same procedure was repeated to get first six mode shapes and natural frequencies. It has been found that the vibration response of glass fibre blade is better compare to blade made of stainless steel. Also considerable weight reduction is achieved due to low density of glass fibre.

2. LITERATURE REVIEW

Standards/Manuals/Guidelines For Small Hydro Development, “*Electro-Mechanical Works – Guidelines for selection of Turbine and Governing System for SHP*” has enlightened on types, classification and performance of various turbines.

Teodor Miloş, Mircea Bărglăzan, “*Cad Technique Used To Optimize The Francis Runner Design*”, this paper illustrates the technique that has been used to build the blade in CATIA.

Gizem Okay, “*Utilization Of CFD Tools In The Design Process Of A Francis Turbine*” has various formulae as well as examples of turbine design.

Jitendra Kumar Sahu, Brijesh Patel, “*Vibration Analysis of Turbine Blades –Using ANSYS*”, has discussed vibration analysis of turbine blades with various alloy steels, aluminium etc.

3. CALCULATION OF BASIC DIMENSIONS

To build the 3D model in CATIA we need to obtain few basic dimensions as shown in the fig 1. To start with following input parameters of Devighat power station have been considered.

Power $P_d = 4.8 \text{ MW} = 4800 \text{ kW}$

Specific Speed, $n_q = 278 \text{ MHP}$

Design Head, $H_d = 40 \text{ m}$

Fig.1 Various Dimensions of Francis Turbine

Rotational Speed of Runner (n):

$$n = n_q (H_d^{1.25} / P_d^{0.5}) \dots \text{Eqn.1}$$

$$= 403.6 \text{ rpm}$$

Angular Rotational Speed of Runner (ω):

$$\omega = 2\pi n / 60 \dots \text{Eqn.2}$$

$$\omega = 42.26 \text{ rad/sec}$$

Discharge (Q_d) can be found using following relation

$$P_d = \rho g Q_d H_d \eta \dots \text{Eqn.3}$$

$$4800 \times 1000 = 1000 \times 9.81 \times Q_d \times 40 \times 0.91$$

$$\eta = 0.91 \dots \text{assumed}$$

$$Q_d = 13.44 \text{ m}^3/\text{s}$$

Shaft Diameter (D_{shaft}):

$$D_{\text{shaft}} = 105 (P_d / n)^{0.35} \dots \text{Eqn.4}$$

$$D_{\text{shaft}} = 249.77 \text{ mm} = 250 \text{ mm}$$

Determination of the Exit Diameter (D_2):

Meridional flow velocity (V_{2m}) at the runner exit

$$V_{2m} = \text{SQRT}(2gH_d \epsilon) \dots \text{Eqn.5}$$

where the variable ϵ is calculated by the following equation

$$\epsilon^2 = 1.16 \times 10^{-3} [(\delta_r \eta_q / \text{SQRT } k) \tan \beta]^{4/3} \dots \text{Eqn.6}$$

$$(\delta_r = 1, k = 1, \beta = 24.5^\circ) \dots \text{assumed}$$

$$\epsilon = 0.8591$$

$$V_{2m} = 25.966 \text{ m/s}$$

The exit diameter (D_2):

$$D_2 = \text{SQRT}[4Q_d / \pi V_{2m}] \dots \text{Eqn.7}$$

$$D_2 = 0.8118 \text{ m} = 811.8 \text{ mm} = 812 \text{ mm}$$

Determination of the Inlet Diameter (D_1)

$$V_{1m} = V_{2m} = 25.966 \text{ m/s} \dots \text{assumed}$$

The inlet circumferential velocity (u_1),

$$u_1 = V_{1m} / 2 \tan \beta_1 + \text{SQRT}[(V_{1m} / 2 \tan \beta_1)^2 + gH_d \eta] \dots \text{Eqn.8}$$

$$(\beta_1 = 83^\circ) \dots \text{assumed}$$

$$u_1 = 20.6 \text{ m/s}$$

The inlet diameter,

$$D_1 = 2 u_1 / \omega \dots \text{Eqn.9}$$

$$= 0.9749 \text{ m} = 974.9 \text{ mm} = 975 \text{ mm}$$

Determination of the Wicket Gate Height (b_0):

$$A_1 = (\pi D_1) b_0 \dots \text{Eqn.10}$$

$$Q_d = A_1 V_{1m} \dots \text{Eqn.11}$$

Hence,

$$b_0 = Q_d / (\pi D_1 V_{1m})$$

$$b_0 = 0.169116 \text{ m} = 169.116 \text{ mm} = 170 \text{ mm}$$

3.1 Thickness of Turbine Blade

Fig 2 shows the relationship between % camber length and the thickness in terms of % of camber length. From CATIA model we have measured camber length which is 191.145 mm. The maximum thickness of the aerofoil is at the 40 % of camber length measured from the leading edge. Hence from above graph the thickness for 40% of camber length is given as follows:

Thickness = 6 % of the camber length

$$= 0.06 \times 191.145 = 11.47 \text{ mm} \sim 12 \text{ mm}.$$

Since we are not dealing with any CFD elements, the blade of single uniform thickness is modelled in CATIA.

Fig.2 Thickness v/s Camber Length

4. GENERATION OF CAD MODEL

Dimensions required for modelling are calculated in the earlier steps. The calculated dimensions are fitted to match fig 6 meridional views. Further CAD model of a blade have been prepared in CATIA. Fig 4, 5 & 6 are important to build 3D model in CATIA whereas fig 3 shows isometric view of turbine along with shaft and blade.

Fig.3 Isometric View

Fig.4 Meridional Plane View

Fig.5 Plan View

Fig. 6 Meridional Views

Following are various views of blade modelled in CATIA

Fig. 7 CATIA Model of Blade of Francis Turbine with Hub, Shroud and Shaft

Fig. 8 Front View of Blade in CATIA

Fig. 9 Top View of Blade in CATIA

Fig. 10 Side View of Blade in CATIA

5. FINITE ELEMENT MODELLING AND MODAL ANALYSIS OF BLADE

Initially the .igs file from CATIA is imported to the meshing software Hypermesh. The CAD data of the blade is imported and the surfaces were created and meshed with Solid 45 (3D Mesh Element Type). Fig 11 shows meshed blade model. The model is imported in ANSYS to perform modal analysis and various mode shapes and their respective natural frequencies are obtained. Initially modal analysis is performed on blade with stainless steel material & later it is performed on blade of glass fibre.

Fig. 11 Meshed Blade (Element Type- Solid 45)

Fig. 12 Meshed Blade with Boundary Conditions

Fig. 14 Mode shape 2 with frequency 1981.94 Hz

Table 1 Properties of Stainless Steel

Property	Value
Young's Modulus	200 Gpa
Poisson's Ratio	0.29
Density	8000 kg/m3
Yield Stress	215 Mpa
Ultimate Tensile Strength	505 Mpa

Fig. 15 Mode shape 3 deflection with frequency 2496.55 Hz

Table 2 Properties of Glass Fibre

Property	Value
Young's Modulus in X Dir.	40300 Mpa
Young's Modulus in Y Dir.	6210 Mpa
Young's Modulus in Z Dir.	40300 Mpa
Poisson Ratio	0.2
Density	1.9×10^{-9} tonne/mm3
Shear Modulus in XY Plane	3070 Mpa
Shear Modulus in YZ Plane	2390 Mpa
Shear Modulus in XZ Plane	1550 Mpa

Fig. 16 Mode shape 4 deflection with frequency 2997.58 Hz

a) Mode Shapes & Natural Frequencies of Stainless Steel Blade

Fig. 13 Mode shape 1 with frequency 1297.82 Hz

Fig. 17 Mode shape 5 with frequency 3926.89 Hz

Fig. 18 Mode shape 6 with frequency 4411.42 Hz

Fig. 22 Mode shape 4 frequency 1602.34 Hz

b) Mode Shapes & Natural Frequencies of Glass Fibre Blade

Fig. 19 Mode shape 1 with frequency 646.989 Hz

Fig. 23 Mode shape 5 with frequency 1954.30 Hz

Fig. 20 Mode shape 2 with frequency 1013.45 Hz

Fig. 24 Mode shape 6 with frequency 2235.86 Hz

Fig. 21 Mode shape 3 with frequency 1231.17 Hz

Table 3 Comparison of Natural Frequencies

Sr. No	Mode	Frequency in Hz	
		Stainless Steel	Glass Fibre
1	1	1297.82	646.989
2	2	1981.94	1013.45
3	3	2496.55	1231.17
4	4	2997.58	1602.34
5	5	3926.89	1954.30
6	6	4411.42	2235.86

6. CONCLUSIONS

- The comparison, between modal analysis results of turbine blade with Stainless Steel

and Glass Fiber as materials, has been performed and it is summarized in table shown above.

- Frequencies of vibration of the composite turbine blade in six different modes are lower than that of Stainless Steel turbine blade.
- Glass Fibre is proven to be better in damping behaviour.
- From CATIA model it is seen that approximately 75% weight of the blade can be reduced using Glass Fibre of same dimensions as of Stainless Steel.
- Further the frequencies obtained for Glass Fibre through modal analysis need to be verified experimentally.
- Detail study with respect CFD considerations & accordingly fatigue analysis shall be considered as future research work.

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