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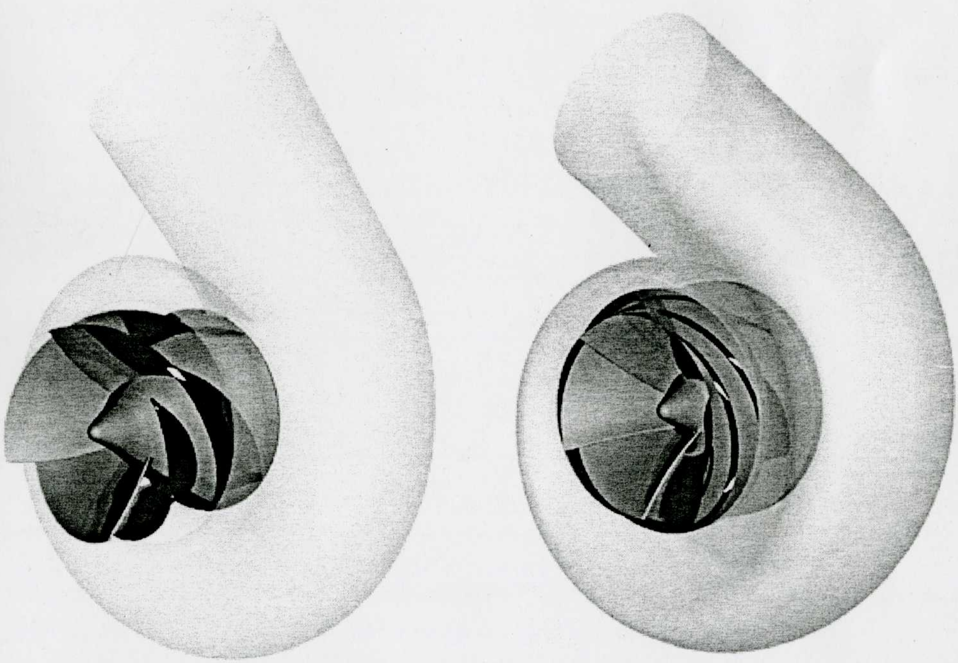

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CONTENTS

DESIGN AND CONSTRUCTION OF MAIN CASING FOR FOUR JET VERTICAL PELTON TURBINE

Prakash K. Dhakan*, Abdul Basheer Pombra Chalil*

Casing is an important part of Vertical Pelton Turbine unit, which acts as a housing for runner and the support for Generator. The design of casing requires consideration of hydraulic as well as mechanical aspects. The size and shape of the casing should be designed to give proper guidance to water flow. Casing should have enough strength to meet the mechanical/structural requirements such as to withstand the dead weight of the generator, forces developed in the manifold/branch pipes, load due to the four jets in different combinations and load due to various actuation mechanisms. After satisfying above aspects, the casing should be checked for vibration behavior by modal analysis. The design of casing for four jet vertical Pelton turbine is carried out considering all above mentioned criterion. Ansys Mechanical software is used to study the structural behavior of casing and also for weight optimization by reducing the thickness of casing and changing arrangement of ribs.

Keywords: *vertical Pelton turbine, turbine casing, Ansys Mechanical, structural analysis, modal analysis*

1. Introduction

Pelton turbine has been in use for more than 100 years and obviously belongs to the most important hydraulic turbines. Pelton turbines are used for the conversion of hydraulic energy in to electricity in mountain areas, where large altitude difference between water sources and sites of Pelton turbines exists. In special applications, the altitude, i.e. the hydraulic head even goes up to 1800 meters [1].

Hydro power is eminent renewable energy source to suit higher energy demand of the world. Pelton turbine is useful to develop power using hydraulic energy in the case of high heads available. In Pelton turbines, water leaving the penstock is directed by a nozzle having an adjustable outlet in a thin jet against the buckets arranged around the periphery of the runner. Generally two types of arrangements are used in Pelton turbines: Horizontal shaft and Vertical shaft arrangement. The horizontal positioning of the shaft permits the application of several runners, whereby higher specific speed and, consequently, higher operational speed can be attained. With vertical shaft arrangement the multi jet construction leads to enhancement of the speed [2].

Pelton turbine consists in four major components i.e. branch pipe (manifold), nozzle, bucket and housing. Each component is playing a significant role for better performance of machine, hence optimized design is required. The casing is an essential part of the turbine. It has to drain off the water coming out of the buckets without hindering the runner. Casing

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should have enough strength to meet the mechanical/structural requirements. In the present paper, the design and analysis has been carried out for main casing for four jet vertical Pelton turbine. Structural and vibrational behaviour of casing is analysed by use of Ansys Mechanical software.

2. Turbine casing

Casing is an important part of Vertical Pelton Turbine unit, which acts as a housing for runner and nozzle tips and the support for Generator. The bottom of the casing is supported on a base frame anchored by bolts to the concrete structure. Casing is cast or fabricated and is usually stiffened with ribs. Internal surfaces of casing should be designed to prevent the water, leaving the buckets, deflected back against the runner. The concrete masses surrounding the branch pipe/manifold and covering the steel housing augment the weight of the substructure and so can contribute to the damping of the vibration. If in addition the weight of the generator has to be transmitted by the casing and its concrete surroundings to the foundation, these structure have to be dimensioned for taking the load over the pit along with the inlet flume and for withstanding the short-circuit torque [2]. The branch pipe/manifold is either mounted on the casing or embedded in the concrete.

3. Hydraulic design of casing

The design of casing has been carried out to satisfy the hydraulic requirements. There are mainly two types of cross section of casing are considered, which are circular and polygonal [2]. Here we selected a circular cross section due to easiness of manufacturing and for smooth profile of internal surface. By means of regression analysis of data pertaining to existing plants, evolved a very close correlation between the casing diameter and the Pelton wheel diameter of vertical shaft arrangement [2]. The casing diameter should be at least 2.5 times the runner pitch diameter to ensure escape of the water [3]. To decide the height of casing, the hydraulic as well as the site operational conditions are considered. The portion of casing above the jet is kept to a minimum width to reduce windage losses but sufficient to free the water coming from buckets. The bottom portion of the casing is kept large enough to insure free discharge from the buckets.

Main hydraulic dimensions of casing can be derived with reference to the following empirical formulae [3]. Fig. 1 shows the main hydraulic dimensions of the turbine casing.

Casing inside diameter

$$L = 2.5\, D_0 \quad [m]\ . \tag{1}$$

Height of casing above nozzle

$$H_{\mathrm{r}} = 0.45\, D_0 \quad [m]\ . \tag{2}$$

Setting height of casing

$$H_{\mathrm{s}} = (0.5{-}1.0) + 0.50\, D_0 \quad [m] \tag{3}$$

where D_0 is the pitch circle diameter of the runner

4. Mechanical design of casing

After finalizing the basic dimensions of the casing from the hydraulic design, the next step is to perform the mechanical design to satisfy the various structural aspects. The first step of the design is to find out the required shell thickness to withstand the various loads acting on the casing. Casing should have enough strength to meets the mechanical/structural requirements such as to withstand the dead weight of the generator, forces developed in the manifold/branch pipes, load due to the four jets in different combinations and load due to various actuation mechanisms [4]. The value of the various loads acting on the casing is shown in Table 1.

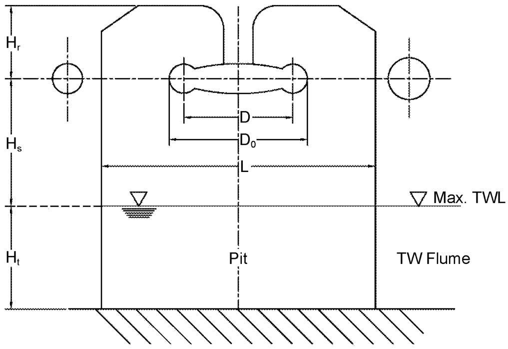


Fig.1: Main hydraulic dimensions of turbine casing

SI No.	Types of Load Acting on the Casing	Value	Unit
1	dead weight of the generator	301.65	kN
2	max. force acting from the branch pipes	200	kN
3	max. load due to four jets	120	kN
4	load from the deflector actuation mechanism	185	kN
5	short circuit torque	468.54	kNm

Tab.1: Value of the various loads acting on the casing

In the first stage of the design, the shell thickness is derived using the analytical equation to withstand the various load acting on the casing [5]. Ribs are provided on the periphery of the casing for structural requirements. Different provisions for inserting the four jets and break jet are provided on the periphery of the casing.

The material of casing is Hot Rolled Medium Structural Steel (ISPL Fe 410 WB, IS: 2062-2006). The Mechanical properties of this material are as follows according to Indian Standard IS: 2062-2006.

Yield tensile strength (min)	:	230 MPa
Ultimate tensile strength (min)	:	410 MPa
Young's modulus	:	200 GPa
Percentage elongation (min)	:	23 %
Poisson's ration	:	0.30
Density	:	7850 kg/m^3

In designing parts to resist failure, it is assured that the internal stresses do not exceed the allowable limit of stresses of the material. If the material to be used is ductile, then it is the yield strength that designer is usually interested in, because a permanent deformation would constitute failure. The distortion- energy theory is also called the Von-Mises theory, which is the most suitable theory to be used in ductile materials [5]. According to distortion-energy theory, allowable stress in order to avoid fracture is equal to yield stress strength. Factor of safety can be calculated by dividing yield stress to maximum Von-Mises stress [6].

5. Structural analysis

Static structural analysis is carried out using finite element method. This analysis is done by Ansys Mechanical version 13 software. The main aim of this analysis is to optimize the casing design by reducing the thickness of casing and ribs through the visualization of the structural behaviour like deformation and the stress level at various locations of the casing. Details of various steps involved in the structural analysis of casing are explained below.

5.1. Modelling

After preliminary mechanical design, a three dimensional (3D) model is made through Pro/Engineer software by keeping all the provisions for design, assembly and operational aspects. This 3D model is used for structural analysis of casing. Fig. 2 shows the 3D model of casing after final optimization is done.

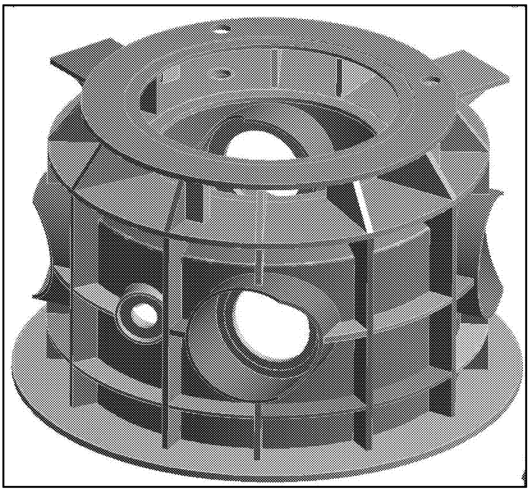


Fig.2: 3D Model of the casing

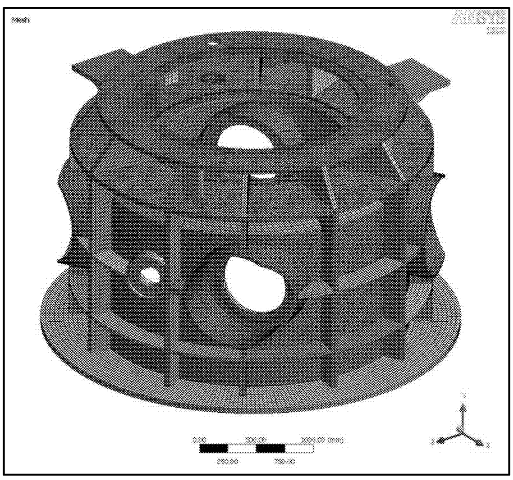


Fig.3: Meshed geometry of the casing

5.2. Meshing

The meshing of the casing is done in the Ansys Mechanical software. The meshed geometry of the casing contains 266039 quadratic elements and 483398 numbers of nodes. Fig. 3 shows the meshed geometry of the optimized casing.

5.3. Boundary condition

The dead weight and the short circuit torque of generator are applied on the top face of the casing, while the loads due to the branch pipe and the load from the four jets are applied on the periphery of the casing. The force acting due to the deflector actuation mechanism is applied on the bracket attached on the casing. Fig. 4 shows the geometry of the casing with different applied boundary conditions.

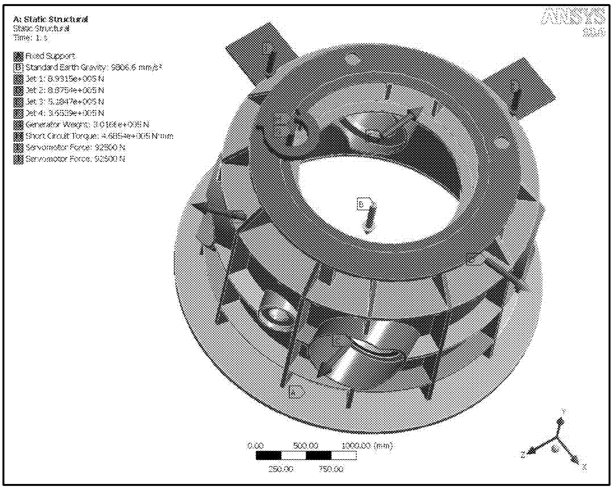


Fig.4: Casing with different applied boundary conditions

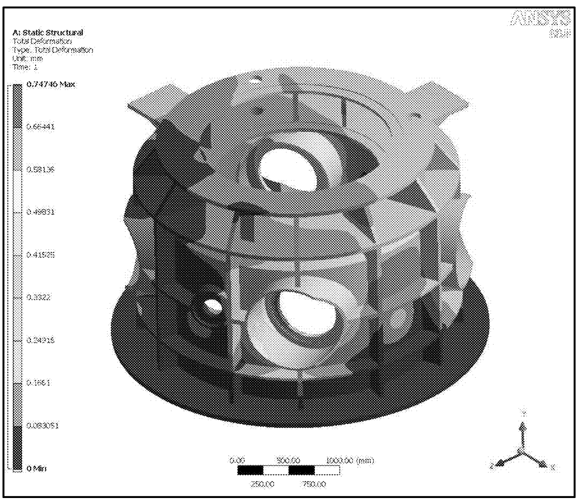


Fig.5: Deformation of casing

5.4. Structural Behaviour

The structural behaviour is analysed by visualising the deformation and the stress levels in the casing. It is found that the dead weight of the generator is mainly transmitting to the foundation through the ribs provided on the periphery of the casing. So it is important to consider the structural behaviour of the rib also. Fig. 5 shows the deformation of casing and Fig. 6, 7 and 8 shows the Von-Mises stress levels in the casing.

Large number of analyses are carried out for different shell and rib thickness of the casing. In each case the deformation and stress level in the casing is noted. The final geometry with shell thickness of 25 mm is selected, which have the deformation and stress value within the safe level. The maximum value of Von-Mises stress by considering the localised stress concentration value is obtained as 119.59 N/mm^2. Through the above analysis the shell thickness is reduces without much increase the stress level. Almost 12 % of weight reduction in comparison with initial design is achieved through this analysis.

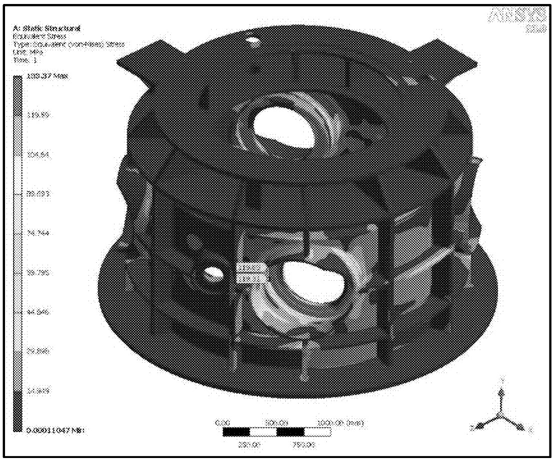


Fig.6: Von-Mises stress in the casing

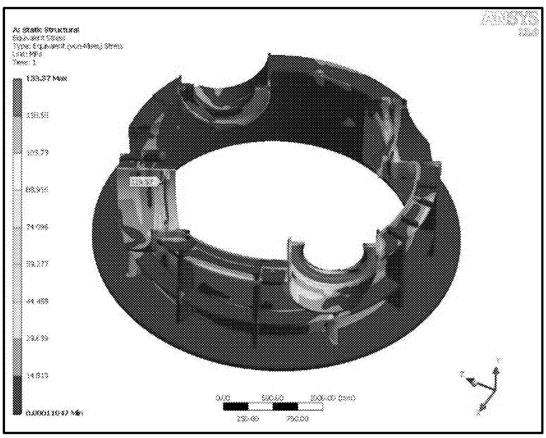


Fig.7: Von-Mises stress in the horizontal cross-section of casing

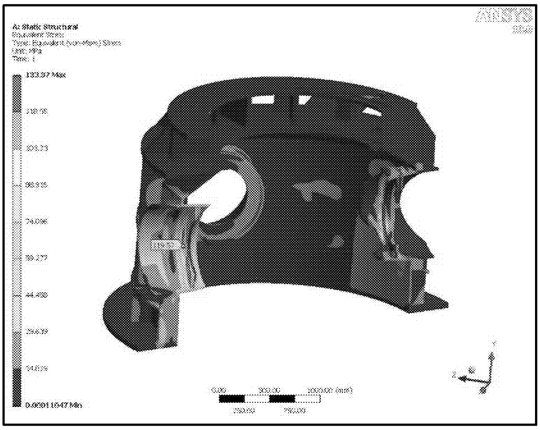


Fig.8: Von-Mises stress in the vertical cross-section of casing

Factor of safety is calculated by dividing actual yield strength of material to Von-Mises Stress obtained from structural analysis.

$$\text{Factor of safety} = \frac{\text{Yield strength of material}}{\text{Von-Mises stress}} \, .$$

The safety factor criteria based on above equations is kept as 2.

6. Modal analysis

To check the dynamic behaviour of the casing, the modal analysis is performed with first 6 number of modes for each iteration. Model Analysis is also carried out by using the software Ansys 13.0. The values of first six number of modes of frequencies are shown in Table 2. Operation frequency of unit is 7.42 Hz and the first mode of natural frequency occurs above 1.3 times of the runaway speed, so the results are satisfactory. Fig. 9 shows the images of model shapes of final optimized geometry for first few modes.

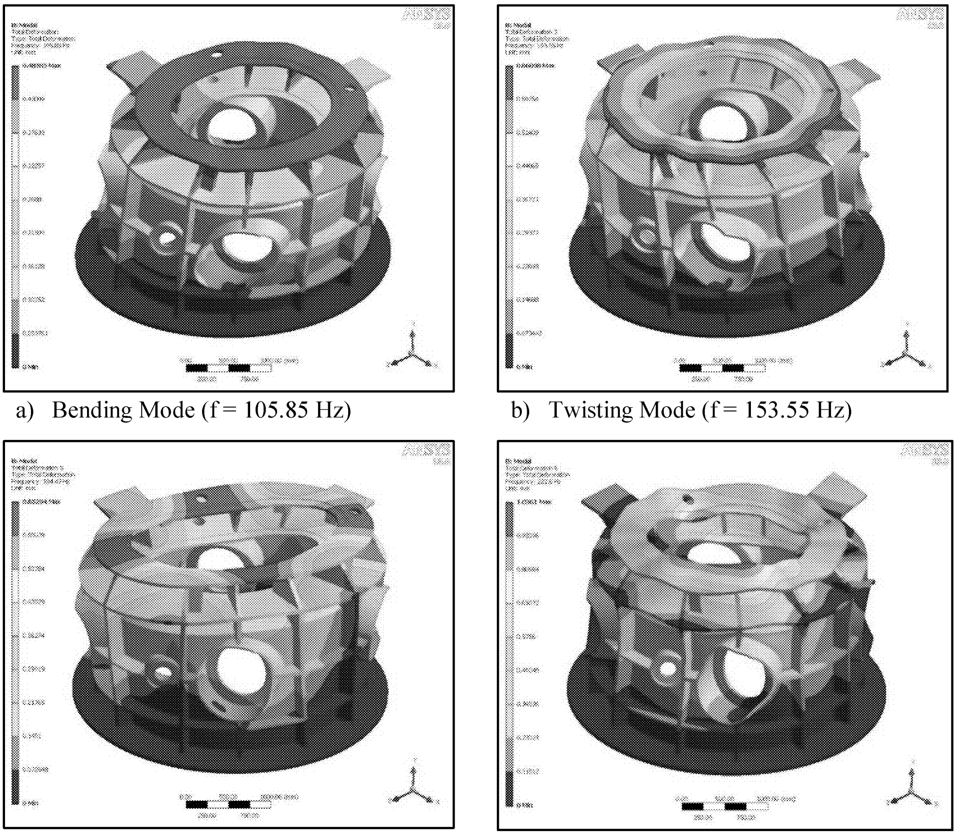
Mode	**Frequency [Hz]**
1	105.85
2	106.89
3	153.55
4	185.28
5	194.43
6	222.60

Tab.2: 6 lowest frequencies for model analysis of the casing

7. Optimization of turbine casing

The aim of this analysis is to optimize the design of casing. Here, the main optimization criteria is reduction of weight of casing by reducing the shell thickness and number of ribs by consideration of structural behaviour within permissible limits.

By keeping above parameters in mind, the preliminary design of casing is carried out after finalizing the hydraulic dimensions. In primary design, shell thickness of casing is



a) Bending Mode (f = 105.85 Hz) b) Twisting Mode (f = 153.55 Hz)

c) Tensile Stretching Mode (f = 185.28 Hz) d) Compressive Mode (f = 222.60 Hz)

Fig.9: Different mod shapes of casing

considered without any vertical or horizontal ribs. Fig. 10 shows the geometry of casing after primary design.

After primary design, structural analysis is carried out to find out the stress and deformation values. It is found that the stress and deformation are very low, however, the total weight of casing is very high. As an optimization stages in order to reduce the weight, different alternative geometries of casing are made and analysed through structural analysis. Different optimization stages selected for modelling and analysis are given in Table 3.

No.	Optimization stages
1	Varying shell thickness without using vertical and horizontal ribs
2	Keeping optimum shell thickness constant and varying nos. of vertical ribs
3	Keeping optimum shell thickness and nos. vert. ribs constant and varying nos. horiz. ribs
4	Keeping optimum nos. of vert. ribs and horiz. ribs constant and varying shell thickness

Tab.3: Different stages of optimization for casing design

In each stage large numbers of analysis are carried out and the best geometry is selected for the next optimization stage. Fig. 11 shows the geometry of casing at the intermediate stage of optimization having only vertical ribs and Fig. 12 shows the final optimized geometry having combination of vertical and horizontal ribs.

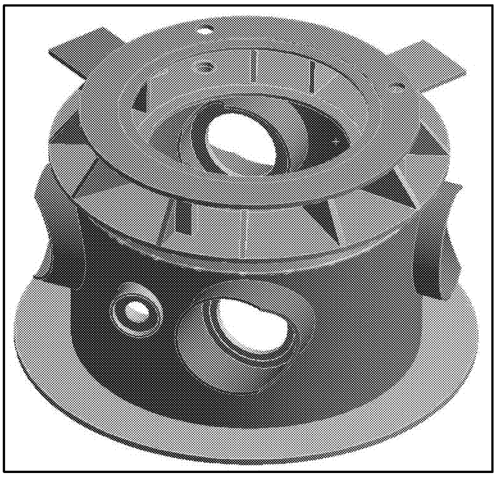


Fig.10: Shape of casing after primary design stage

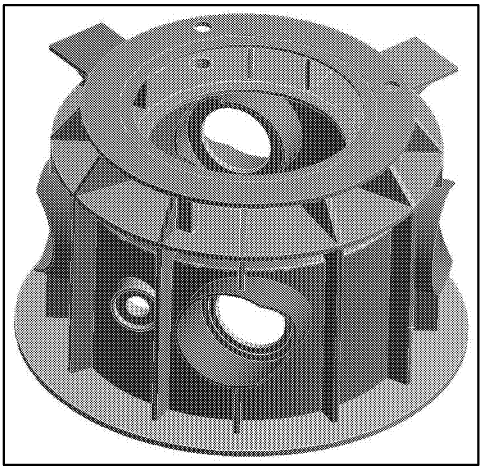


Fig.11: Shape of casing at the intermediate stage of optimization

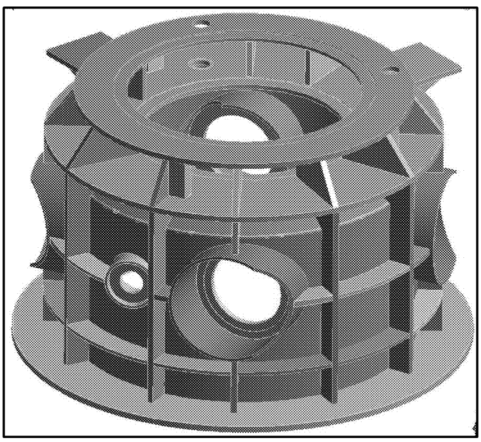


Fig.12: final optimized shape of casing

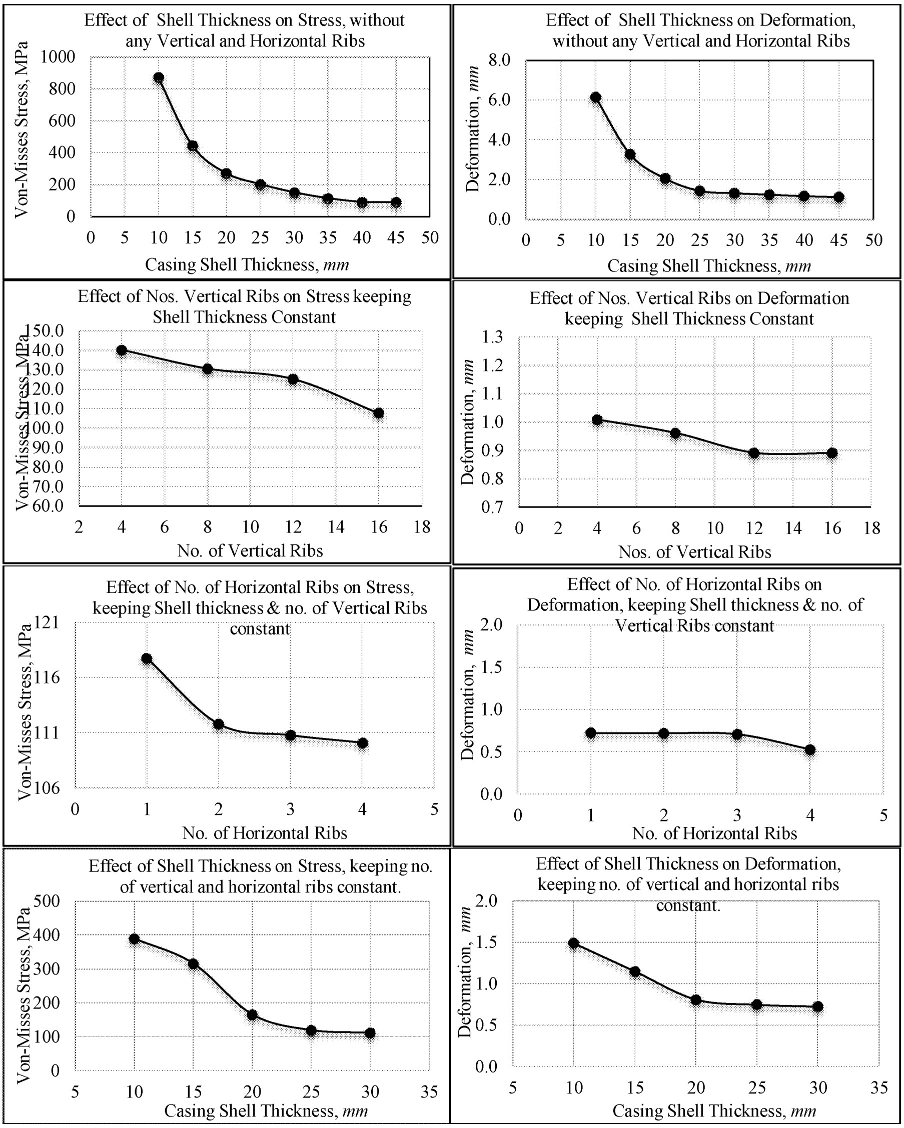


Fig.13: Effect of shell thickness and no. of ribs on stress and deformation

The main constraint for optimization criteria is the factor of safety based on von-misses stress and deformation of casing due to various loads acting on it. The minimum factor of safety is considered as the 2 and allowable deformation of 1.25 mm is taken by considering the limitation of assembly and functional requirements. In the each stage of the optimization, number of analyses are carried out by varying the casing parameters like thickness and numbers of vertical and horizontal ribs. Results of each analysis are compared with the above optimization criteria. The geometry which is having the lowest weight and also satisfying the optimization criteria (i.e. minimum factor of safety of 2 and allowable deformation of 1.25 mm) is to be considered for the next stages of optimization. However, to check the possibility of weight optimization, the next lower size of optimized geometry is considered for every new optimization stage. The model analysis is carried out during every stages and the frequencies are verified with the maximum operating frequency of the unit. It is found that for all different combinations of casing geometries, the first natural frequency is higher than 1.3 times of runaway speed of the unit. At the end of the optimization stage, the geometry having minimum weight and satisfying the optimization criteria is selected for the manufacturing. Fig. 12 shows the picture of final geometry of casing, which is the optimized geometry, having shell thickness of 25 mm and number of vertical and horizontal ribs are 12 and 2 respectively. The von-misses stress of 119.59 MPa and deformation level of 0.747 mm are observed, which are within acceptable limit. A weight reduction of 1770 kg is achieved through this optimization analysis. This weight reduction is for finished geometry of casing, however considering gross weight of raw material, the actual weight reduction is achieved nearly 2100 kg. The details and results of each optimization steps are given in below Table 4.

Shell thickness (mm)	Nos. of vertical ribs (nos.)	Nos. of horizontal ribs (nos.)	Von-Misses stress (MPa)	Deflection (mm)	Factor of safety (–)	Weight (kg)	Frequency (Hz)
Stage 1: Varying shell thickness without using vertical and horizontal ribs							
45	0	0	90.44	1.118	2.65	15395	89.41
40	0	0	92.71	1.168	2.59	14680	83.57
35	0	0	115.69	1.240	2.07	13850	77.55
30	0	0	152.85	1.316	1.57	13035	71.33
25	0	0	204.07	1.435	1.18	12220	65.15
20	0	0	272.60	2.058	0.88	11405	58.89
15	0	0	446.15	3.271	0.54	10590	52.05
10	0	0	871.79	6.158	0.28	9775	43.89
Stage 2: Keeping shell thickness constant and varying nos. of vertical ribs							
30	4	0	140.25	1.010	1.71	13575	104.56
30	8	0	130.68	0.962	1.84	14102	114.25
30	12	0	125.35	0.893	1.92	14656	120.71
30	16	0	107.86	0.891	2.23	15226	121.54
Stage 3: Keeping shell thickness and nos. vertical ribs constant and varying nos. horizontal ribs							
30	12	1	121.15	0.726	1.98	14874	115.74
30	12	2	111.81	0.724	2.15	14990	115.99
30	12	3	110.79	0.712	2.17	15170	116.07
30	12	4	110.12	0.530	2.18	15348	116.15
Stage 4: Keeping nos. of vertical ribs and horizontal ribs constant and varying shell thickness							
30	12	2	111.81	0.724	2.15	14990	115.99
25	12	2	119.59	0.747	2.01	12080	110.01
20	12	2	165.73	0.810	1.45	11427	102.78
15	12	2	316.23	1.150	0.76	10765	93.74
10	12	2	389.81	1.490	0.62	10102	82.27

Tab.4: Results of different optimization stages of casing

Fig. 13 shows the effect of various casing parameters on the stress and deformation which are mentioned in Table 4. From these graphs, it is very clear that varying shell thickness of casing have large impact on stress and deformation. However after a certain value of shell thickness, increase of thickness is not affecting much on stress and deformation values. Addition of vertical ribs and horizontal ribs also have significant role in reduce stress and deformation which helps for optimization of overall geometry of casing.

The dimensions of preliminary and final design of the casing as follows,

Case 1: Preliminary design

Shell thickness	35	mm
Nos. of horizontal ribs	0	–
Nos. of vertical ribs	0	–
Finished weight	13850	kg

Case 1: Final design

Shell thickness	25	mm
Nos. of horizontal ribs	2	-
Nos. of vertical ribs	12	–
Finished weight	12080	kg

8. Conclusion

Design of main casing for four jet Vertical Pelton Turbine is carried out by considering the hydraulic and mechanical aspects. All hydraulic parameters are taken care during hydraulic design, while structural, manufacturing, assembly and operational parameters are considered during the mechanical design of the casing. Through the structural analysis using Ansys Mechanical software, casing design is optimized and a weight reduction of around 12 % is achieved. Vibration behaviour of the casing is analysed through the model analysis and ensured the natural vibration of casing is well above the operating frequency of turbine unit.

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