Optimization of Strain Gauge Location for Combined Centrifugal and Vibratory Stresses on Steam Turbine Blade

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Abstract-- The 6th stage steam turbine blade rotating with rotation velocity is deeply analyzed and analysis is carried out as described below. In this paper the optimum point is found out to mount strain gauges on the turbine blade for the combined centrifugal and vibratory stresses in steam turbine engines in order to capture the best modal response in the series of modes. In the first part modal analysis was carried out for free-free vibration and there was good agreement between the experimental and finite element analysis results and the deviation was found to be within 10%. In the second part the rotation velocity of 10000 RPM was given and vibratory stresses were calculated using harmonic analysis for 5 modes and corresponding centrifugal stresses were found for 5 modes. Then the relative percentages of stresses were located for different nodes on the blade on both concave and convex side of the blade to find optimal location on the blade. The optimum point on the concave side was found at the node 10.93, 306.27,-21.749 at the point x, y, z respectively and at this point 42%,26%,22%,15.3 and 7% of stress were captured and the optimum point on the convex side found at the node-7.709,312.83,0.844 at the point x, y, z respectively and at this point 36.6%,19.8%,19.8%,25.14%,4.7% of stresses were captured.

Keywords - Blade vibration; Static-structural analysis; Modal analysis; harmonic analysis; optimum point investigation

I. INTRODUCTION

Many issues have been reported with respect to turbine blade vibration and locating the optimum point on the blade to fix the strain gauges. Though much of the work is not done on finding the optimum point, this paper shows the establishing the procedure to locate the optimum point on the blade through manual calculations. Aarash Rahmani et.al [1] investigated that among the different failure that occur in the turbine blade, the resonant vibration was the most critical one. Natural frequency and modes shapes were calculated to study the dynamic characteristic or vibration characteristic of the turbine blade. S.Narasimha G. et.al [2] investigated the frequency response of the blade with and without the damper at different angular velocities. The results obtained are analyzed for assessing the efficacy of the elements in yielding the natural frequencies, mode shapes and the response of the vibrating blades. Marc P. Mignolet et.al [3] proposed the formulation and validation of an automatic strategy for the selection of the locations and directions of strain gages to capture the best modal response of a blade in a series of modes. The literature gap is there is lot of journals which shed light on static, modal and harmonic analysis but there is also lack of theory regarding the finding of optimum point to fix the strain gauges on the steam turbine blades so that the strain gauge shall pick up all the stresses and strain to the maximum extent from all the centrifugal and vibratory stresses on the convex and concave sides of the blade. The main objective of the project is to validate the result for free-free vibration and optimization of the strain gauge location on the turbine blade to capture the best modal response in the series of modes.

II. ANALYTICAL MODELING, DESIGN MODIFICATION AND EXPERIMENTATION

2.1. Experimental Modal analysis

The experimental set-up includes Piezoelectric Delta Tron accelerometer, which are installed on the blade and the modal hammer is used to excite the blade. The Delta Tron accelerometer has been connected to the computer which processes the data. Then, ME scope software has been used to get the mode shapes and frequencies. The experimental results are compared with those obtained by finite element based analysis.

To examine the dynamic behaviour, the blade was analyzed in free-free vibration method. The free-free vibration of the single blade is analyzed without any constraints, hanging with an inelastic string and hammer strike performed in single point and accelerometer response is measured at the 30 points marked on the blade.

2.2. Finite element analysis

The steam turbine blade is made of the chromium steel of length 238.89 and width 41.95 of steel grade X22CrMoV12-1 and mechanical properties are as:

Table 1. Properties of X22CrMoV12-1

Young's modulus	Density	Poisons ratio
200 Gpa	7900 kg/m3	0.3

In order to obtain the finite element model, the 3D model of the blade is created in the CATIA V5 and it is imported in to the ANSYS (WORKBENCH 14.5) shown in the Fig 1. To validate the 3D model, the real mass of the blade and this model are compared by performing the free-free vibration analysis and result has less than 10% difference, so, the finite element model which is created by the CATIA V5 is accurate enough and reliable to simulate the real blade behaviour. The SOLID 187 element used for meshing this model is 10 node quadratic tetrahedron structural elements. The Finite Element mesh of the blade has 9855 elements and 17685 nodes. Modal analysis is performed for studying the natural mode shapes and the related frequencies are obtained.

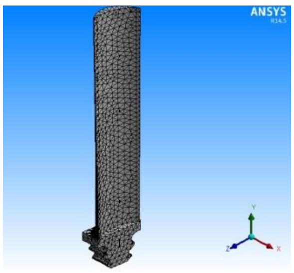


Figure 1.Finite element model with mesh

2.3. TURBINE BLADE WITH ROTATION VELOCITY (RPM)

In order to achieve the optimum point on the turbine blade to mount the strain gauge, the blade was given a rotation velocity of 10000 RPM with clamped boundary condition as real situation or the blade which is installed on the rotor, a steel support as a fixture is used to provide the cantilever beam mode. The natural frequencies and the mode shapes are determined and the harmonic analysis is performed with the harmonic load of 0.5 Mpa. The harmonic stresses (vibratory stress) are determined on both concave and convex side of the blade as shown in the Fig.2 and the corresponding to the points in which the harmonic stresses are found the centrifugal stresses are determined using static-structural analysis. The both centrifugal and harmonic stresses are combined in order to obtain the relative percentages of stress w.r.t combined stresses on the blade for all the modes.

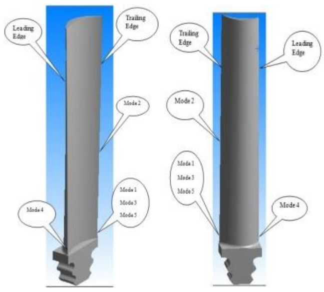


Figure 2.Maximum harmonic stresses on concave and convex side respectively.

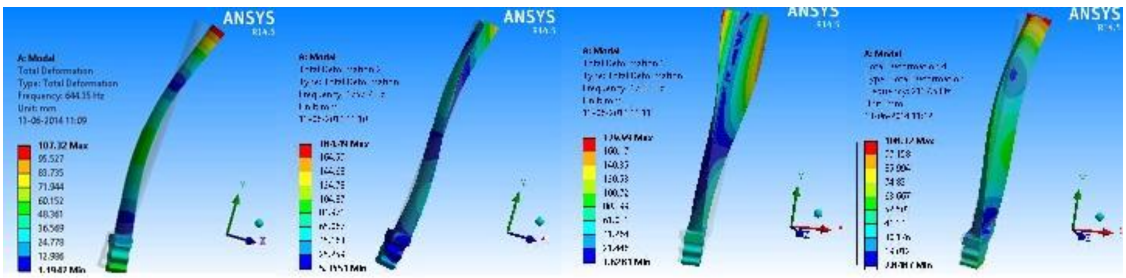
2.4. HARMONIC ANALYSIS

Harmonic load of 0.5 Mpa was applied on the blade and the maximum response was obtained at 350Hz thus very close to modal's first natural frequency. The maximum harmonic stresses for each modes was determined on both concave and convex sides and corresponding centrifugal stress was found at maximum stress location for every modes.

III. RESULTS AND DISCUSSION

3.1 Free-free vibration

In this work, the first five mode shapes obtained for free-free vibration is shown in the Fig 3. Free-free vibration frequencies and related mode shapes, which are obtained by experimental tests compared with the finite element analysis is shown in the Table 2.



Mode1 **Mode 2** **Mode 3** **Mode 4**

Figure 3. Blade Mode Shapes Obtained from FE Analysis.

Table2. Free-free vibration natural frequencies and modes

Mode no.	Natural frequency(Hz)		Deviation (%)	Mode shape
	Experimental	FEA		
1	688.92	644.35	6.4	BEND
2	1568.55	1757.7	10.1	TWIST

3	1893.2	1788	5.5	TWIST
4	2302.68	2137.5	7.1	BEND+TWIST

3.2 Determination of optimum point

In order to determine the optimum point on the blade, the blade rotated at 10000 RPM is analysed and the corresponding natural frequency and mode shapes are shown in the Table 3.

Table 3. Clamped vibration natural frequencies and modes

Mode no.	Natural frequency(Hz)	Mode shape
1	344.31	BEND
2	622.97	EDGE BEND
3	1123.4	BEND
4	1352.6	TWIST
5	2507.3	BEND+TWIST

The maximum number of points are taken on the different locations of the blade to calculate the relative percentages of stresses that are captured for every modes and one point is chose as an optimum point. The calculation for one point is shown in Table 5.Similarly for different points on the blade the calculations are done and one point is chosen. Table 4 shows the combined centrifugal and harmonic stresses on the concave side of the blade. In the same way the points can be calculated for convex side of the blade and find the optimum point.

Table 4. Sum of centrifugal stress and vibratory stress on concave side of the blade

Mode no.	Frequency(Hz)	Location of node (mm)			Node ID	Centrifugal stresses (Mpa)	Maximum harmonic stress(Mpa)	Centrifugal+Harmonic stress(Mpa) (Combined stress)
		X	Y	Z				
1	344.31	11.126	302.7	-22.808	152	530.05	714.98	1245.03
2	622.97	12.389	397.98	-22.079	180	309.19	244.12	553.31
3	1123.4	11.126	302.7	-22.808	152	530.05	261.57	791.55
4	1352.6	4.1447	302.97	22.805	1	250.98	241.15	492.13
5	2507.3	11.126	302.7	-22.808	152	530.05	63.14	593.05

For Example for Node 1 the percentage of stress captured from all the modes is calculated shown in Table 5

Table 5. Sum of centrifugal stress and vibratory stress on concave side of the blade

Node 1	Frequency (Hz)	Harmonic stress (At Node 1)	Combined stress	% of stress= (harmonic stress /combined stress) ×100
Mode 1	344.31	528.2	1245.03	42%

Mode 2	622.97	144.6	553.55	26%
Mode 3	1123.4	173.47	791.55	22%
Mode 4	1352.6	75.4	492.13	15.3%
Mode 5	2507.3	42.98	593.05	7%

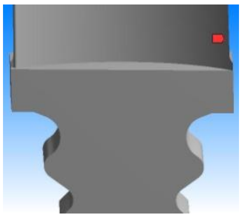


Figure 4. Optimum point to mount strain gauge on the concave side

Table 6. Optimum point node location

X(mm)	Y(mm)	Z(mm)	NODE ID
10.393	306.27	-21.749	4401

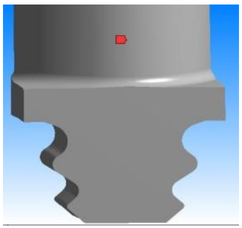


Figure 5.Optimum point to mount strain gauge on the convex side

Table 7. Optimum point node location

X(mm)	Y(mm)	Z(mm)	NODE ID
-7.7807	312.83	0.84434	12635

IV. CONCLUSIONS

Static-structural analysis, modal analysis and Harmonic analysis of steam turbine blade was done using FEA. Analysis was carried for different vibration methods i.e. for free-free vibration, fixed-free vibration and fixed-free vibration with RPM. From the entire research the following conclusions were reported.

- The free–free vibration of a single blade from the finite element analysis results can match very well with the experimental results. The natural frequencies of a single blade obtained from FEM are found within 10% difference compared with the test results. The mode shapes from finite element analysis agree completely with the results obtained in the experimental results.

- Harmonic load of 0.5 Mpa was applied on the blade and the maximum response was obtained at 350Hz thus very close to modal's first natural frequency.

- The optimisation of the strain gauge location was done by the combined centrifugal and vibratory stresses on the concave and convex side of the blade to capture a best modal response on the blade. The optimum point showed on the blade reveals that the maximum percentages of stress were captured at the first mode and the fair amount of stresses was captured at the optimum point from all the 5 modes.

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