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Full Length Research Paper

Prediction of stress concentration effect under thermal and dynamic loads in a high pressure turbine rotor

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Geometric discontinuities cause a large variation of stress and produce a significant increase in stress. The high stress due to the variation of geometry is called as 'stress concentration'. This will increase when the loads are further applied. There are many investigators who studied the stress distribution around the notches, grooves, and other irregularities of various machine components. This paper analyses the effect of stress concentration under thermal and dynamic loads in a steam turbine rotor grooves under the operating conditions. Stresses due to thermal and dynamic loads in high pressure steam turbine rotor of 210 MW power station were found in two stages. A source code is developed for calculating the nominal stress at each groove section of HPT rotor. Maximum stress is obtained using FEA at the corresponding section. Stress concentration factors due to thermal and dynamic loads at each section were calculated. It is observed that the stress concentration due to the combined effect of thermal and dynamic loads is exceeding the safe limits at temperatures beyond 540°C.

Key words: Stress concentration factors, HPT rotor, thermal loads, dynamic loads.

INTRODUCTION

Peterson (1958) did a significant research on stress concentration of various machine components. Neuber (1961) did an exhaustive work on stress concentration factors for extreme thin components. Alexander and Leyzerovich (2007) found that cycling thermal stresses or low-cycle fatigue on steam turbine rotor exceeds prescribed limits that can lead to cracking of the rotors. Gee et al. (2006) worked on the thermal stresses of steam turbines and observed that these are due to the steam flow temperature. Kang and Jong (1996) found that stress intensity factor (SIF) for an embedded elliptical crack in a turbine rotor and thermal shock stress intensity factor for a semi-elliptical surface crack in a finite plate are determined by numerical methods. Shlyannikov et al. (2008) assessed the integrity of cracked steam turbine rotor which operates under creep conditions. Kostyuk (2006) verified results from calculating the long-term strength of single-piece forged rotors using the natural mechanistic procedure are compared with the experimental long-term strength characteristics of the models of high-temperature disk rims and with the field data on failures of such rims.

The contributions of the above in this area are very useful for many investigations. In the literature, it is not available for the cases like determining the stress concentration factors for critical and heavy components such as turbine rotors. Most of the researchers concentrated or limited their works to only one type of analysis such as either static or thermal or dynamic load.

In recent years, there has been an increased interest in the design and analysis of steam and gas turbines. In the power plant applications, a steam turbine rotor is indispensable equipment for power generation. The life of rotors in steam turbines has a severe impact on the power generation system. In the present work, a typical HP turbine rotor considered for the determination of stress concentration factors is described. A theoretical investigation of the turbine rotor using finite element method has been presented. Thermal and dynamic stresses are obtained using finite element analysis.

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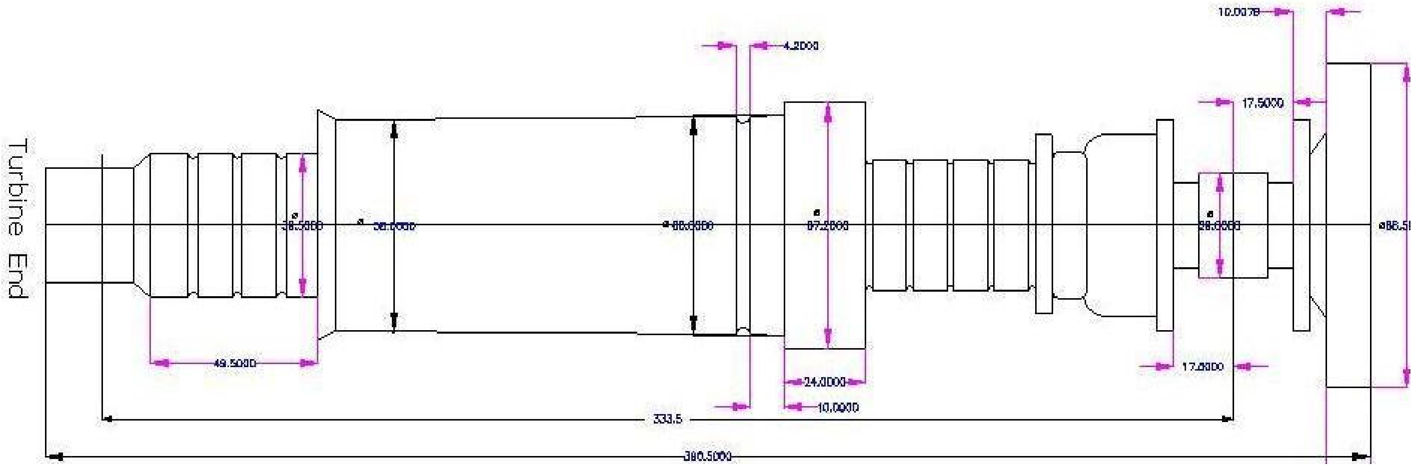

Figure 1. Line drawing of HPT rotor.

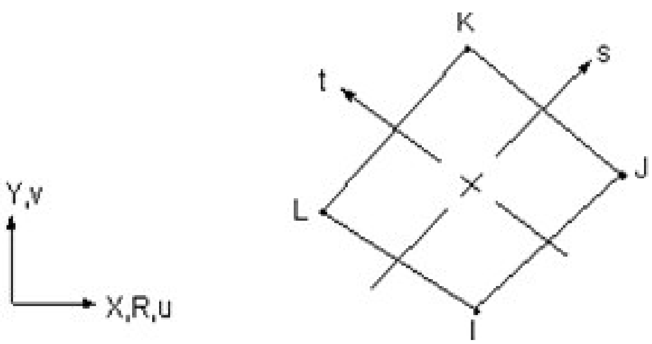

Figure 2. Plane 182 element.

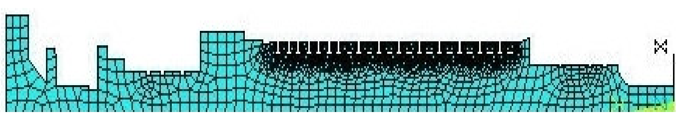

Figure 3. FE model of HP turbine rotor.

Stress concentration factors for thermal and dynamic loads are calculated for HP rotor.

DESCRIPTION

A line diagram of HPT rotor is presented in Figure 1. The geometric and elastic properties and also operating conditions are as follows:

Rated output = 210 MW
Rated speed = 3000 rpm
Inlet steam pressure =150 kg/cm^2 (absolute)
Inlet steam temperature = 535℃
Reheat steam temperature = 535℃
Weight of the unit = 475 tons
Overall length = 16.975 m
Overall width = 10.5 m
Rated frequency = 50 c/s
Maximum permissible speed = 3090 rpm
Minimum permissible speed = 2850 rpm
Maximum frequency = 51.5 c/s
Minimum frequency = 47.5 c/s

MODELING OF THE PROBLEM

The chosen problem is considered as 2-D axi-symmetric problem to reduce the considerable time of computations and tedious computer efforts. The model consists more than 10,000 elements. Figure 2 shows the element 182 considered for meshing. FE modeling of the HP turbine rotor is shown in the Figure 3. Appropriate boundary conditions are incorporated in the analysis. The element can be used as either a plane element (plane stress, plane strain or generalized plane strain) or an axisymmetric element. Axi-symmetric elements are available in most finite element packages and in a range of element shapes and types. No special boundary conditions have to be applied to these elements to achieve the symmetry condition. It is defined by four nodes having two degrees of freedom at each node: Translations in the nodal x and y directions. The element has plasticity, hyper elasticity, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials.

Stress concentration factors for thermal and dynamic loads are computed in terms of stresses developed due to static loading on the rotors, load that is developed due to temperature rise and the load acting on the turbine blades due to steam pressure.

Table 1. Groove number Vs thermal stresses.

Groove no.	Thermal stress (N/m²) ×10⁶				
	530°C	535°C	540°C	545°C	550°C
1	2.229249	2.408066	2.598804	2.801463	3.027964
2	2.422833	2.616144	2.822343	3.054316	3.299177
3	2.632442	2.839178	3.059697	3.307780	3.569646
4	2.804383	3.023476	3.271780	3.534691	3.812208
5	2.994934	3.225314	3.486410	3.762866	4.070039
6	3.143808	3.400445	3.657083	3.961840	4.282636
7	3.296652	3.563048	3.846093	4.162439	4.495434
8	3.437682	3.712696	4.004899	4.331479	4.675247
9	3.566470	3.866618	4.166767	4.502227	4.855343
10	3.682588	3.971418	4.296352	4.639338	5.000376
11	3.785610	4.098014	4.428796	4.777954	5.163865
12	3.893735	4.210450	4.545795	4.899771	5.291008
13	3.950646	4.270460	4.609087	4.985339	5.380403
14	4.030731	4.352432	4.693057	5.071529	5.487849
15	4.077125	4.418466	4.759806	5.139074	5.556268
16	4.108211	4.430052	4.789757	5.168394	5.584894
17	4.123563	4.462486	4.820238	5.196819	5.611058
18	4.141408	4.477198	4.831643	5.223397	5.633807
19	4.105353	4.436727	4.786510	5.173113	5.596535
20	4.089028	4.414703	4.758471	5.138425	5.554565
21	4.036775	4.373173	4.709571	5.099085	5.506303
22	3.966582	4.277010	4.621930	4.984097	5.398001
23	3.878015	4.195611	4.529923	4.897665	5.282124
24	3.786762	4.092926	4.415204	4.769709	5.156442
25	3.659498	3.952875	4.277134	4.616834	4.987416

The software

The problem is analyzed by the software ANSYS 10.0. The flexibility, capability and options made the ANSYS program as user oriented and can be applied to variety of practical problems. The package contains many routines and all are interrelated to achieve a solution to the practical problems by finite element method.

RESULTS AND DISCUSSION

The rotor is cut with 25 grooves stretching over a span of 1.712 m to accommodate the blades. The analysis has been carried-out in two phases. The 1st phase involves thermal analysis and the 2nd phase covers dynamic analysis.

Thermal analysis

Variation of thermal stresses with respect to grooves is shown in Table 1. The results are plotted in Figure 4. Theoretical stress concentration factor based on thermal stress is given in Table 2 and plotted in Figure 5. The way the theoretical stress concentration factor is varying with respect of thermal stresses is shown in the Table 3 and plotted in Figure 6. The thermal stresses are obtained at the elevated temperatures of 530, 535, 540, 545 and 550°C.

It is observed that thermal stresses are increasing from 2.229249 × 10^6 N/m^2 to 4.141408 × 10^6 from the 1st to 18th groove and gradually decreasing to 3.659498 × 10^6 N/m^2 at the temperature of 530°C. At 535°C, thermal stresses are 2.408066 × 10^6 N/m^2 at the 1st groove and gradually increasing to 4.477198 × 10^6 N/m^2 up to 18th groove and gradually decreasing to a value of 3.952875 × 10^6 N/m^2 at 25th groove. At 540°C, thermal stresses are 2.598804 × 10^6 N/m^2 at the 1st groove and gradually increasing to 4.831643 × 10^6 N/m^2 up to 18^h groove and gradually decreasing to a value of 4.277134 ×10^6 N/m^2 to the last groove. It is observed that thermal stresses are increasing 2.801463 × 10^6 to 5.223397 × 10^6 N/m^2 from the 1st to 18th groove and gradually decreasing to a value of 4.616834 × 10^6 N/m^2 to the last groove at the temperature of 545°C.It is observed that the thermal stresses are increased 3.027964 × 10^6 to 5.633807 × 10^6 N/m^2 from the 1st to 18th groove and gradually decreasing to 25th groove to the value of 4.987416×10^6 N/m^2 at the

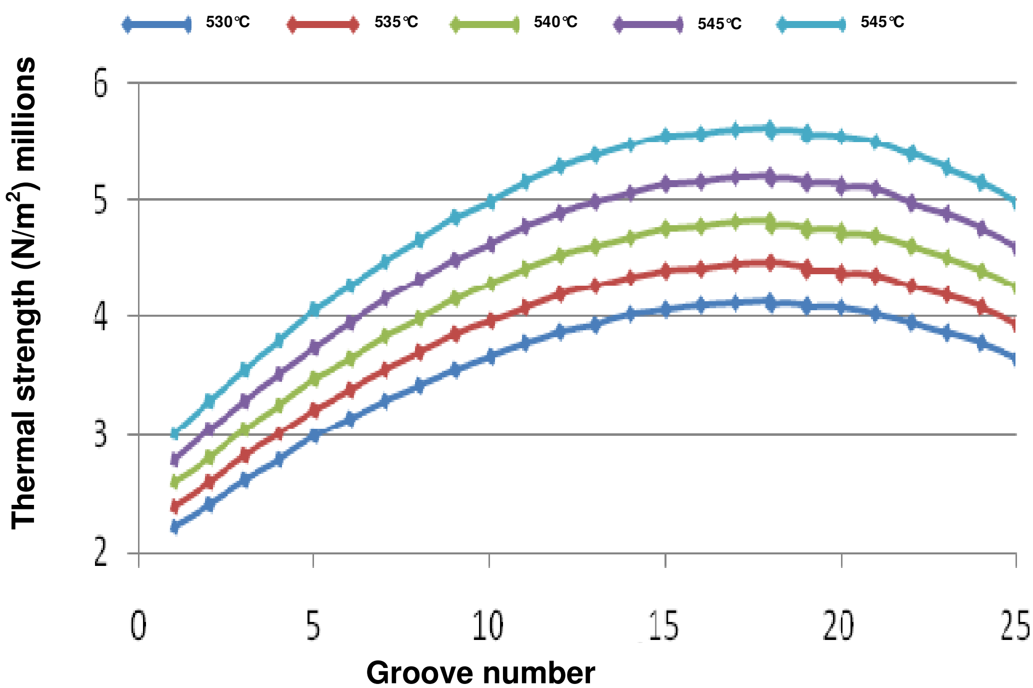

Figure 4. Variation of thermal stresses with respect to groove.

Table 2. Thermal stress vs. theoretical stress concentration factor.

Groove no.	Thermal stress (N/m^2) ×10^6					Theoretical stress concentration factor (K_t)				
	530℃	535℃	540℃	545℃	550℃	530℃	535℃	540℃	545℃	550℃
1	2.229249	2.408066	2.598804	2.801463	3.027964	1.7	1.84	1.98	2.14	2.31
2	2.422833	2.616144	2.822343	3.054316	3.299177	1.71	1.85	1.99	2.15	2.33
3	2.632442	2.839178	3.059697	3.307780	3.569646	1.74	1.87	2.02	2.18	2.35
4	2.804383	3.023476	3.271780	3.534691	3.812208	1.75	1.88	2.04	2.2	2.37
5	2.994934	3.225314	3.486410	3.762866	4.070039	1.77	1.91	2.06	2.23	2.41
6	3.143808	3.400445	3.657083	3.961840	4.282636	1.78	1.93	2.07	2.25	2.43
7	3.296652	3.563048	3.846093	4.162439	4.495434	1.8	1.95	2.1	2.27	2.45
8	3.437682	3.712696	4.004899	4.331479	4.675247	1.82	1.96	2.12	2.29	2.47
9	3.566470	3.866618	4.166767	4.502227	4.855343	1.84	1.99	2.15	2.32	2.5
10	3.682588	3.971418	4.296352	4.639338	5.000376	1.85	2	2.16	2.34	2.52
11	3.785610	4.098014	4.428796	4.777954	5.163865	1.87	2.03	2.19	2.36	2.55
12	3.893735	4.210450	4.545795	4.899771	5.291008	1.9	2.05	2.22	2.39	2.58
13	3.950646	4.270460	4.609087	4.985339	5.380403	1.91	2.06	2.23	2.41	2.6
14	4.030731	4.352432	4.693057	5.071529	5.487849	1.94	2.09	2.25	2.44	2.64
15	4.077125	4.418466	4.759806	5.139074	5.556268	1.95	2.12	2.28	2.46	2.66
16	4.108211	4.430052	4.789757	5.168394	5.584894	1.97	2.13	2.3	2.48	2.68
17	4.123563	4.462486	4.820238	5.196819	5.611058	1.99	2.15	2.33	2.51	2.71
18	4.141408	4.477198	4.831643	5.223397	5.633807	2.02	2.18	2.35	2.55	2.75
19	4.105353	4.436727	4.786510	5.173113	5.596535	2.03	2.19	2.36	2.55	2.76
20	4.089028	4.414703	4.758471	5.138425	5.554565	2.05	2.22	2.39	2.58	2.79
21	4.036775	4.373173	4.709571	5.099085	5.506303	2.07	2.25	2.42	2.62	2.83
22	3.966582	4.277010	4.621930	4.984097	5.398001	2.09	2.25	2.44	2.63	2.85
23	3.878015	4.195611	4.529923	4.897665	5.282124	2.11	2.28	2.46	2.66	2.87
24	3.786762	4.092926	4.415204	4.769709	5.156442	2.14	2.31	2.49	2.69	2.91
25	3.659498	3.952875	4.277134	4.616834	4.987416	2.15	2.33	2.52	2.72	2.94

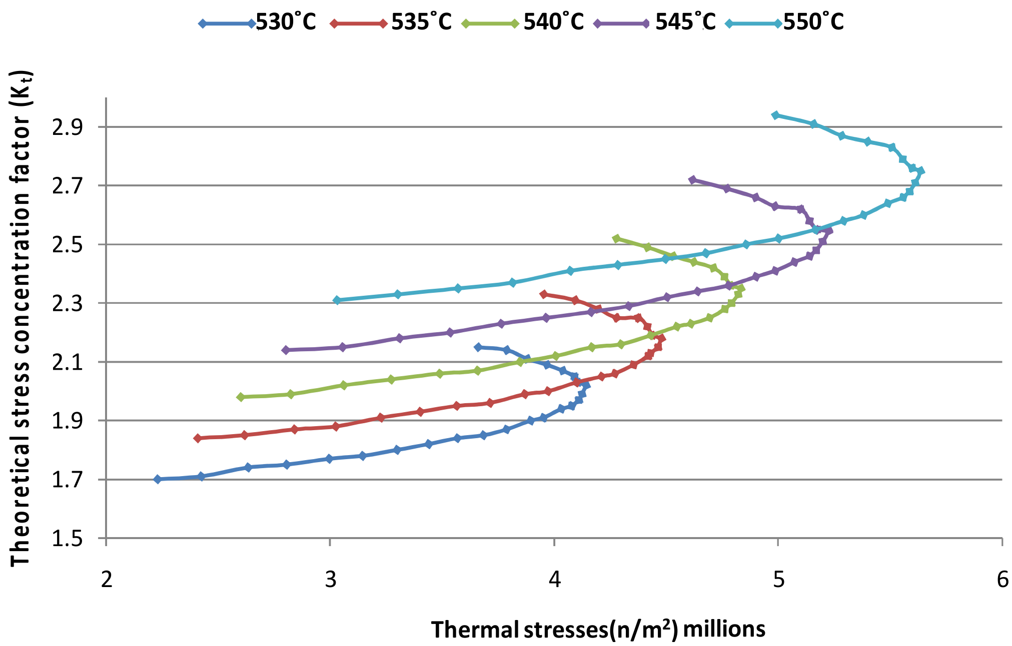

Figure 5. Theoretical stress concentration factor with respect to thermal stress.

Table 3. Grove number vs. theoretical stress concentration factor.

Groove no.	Theoretical stress concentration factor (K_t)				
	530℃	535℃	540℃	545℃	550℃
1	1.7	1.84	1.98	2.14	2.31
2	1.71	1.85	1.99	2.15	2.33
3	1.74	1.87	2.02	2.18	2.35
4	1.75	1.88	2.04	2.2	2.37
5	1.77	1.91	2.06	2.23	2.41
6	1.78	1.93	2.07	2.25	2.43
7	1.8	1.95	2.1	2.27	2.45
8	1.82	1.96	2.12	2.29	2.47
9	1.84	1.99	2.15	2.32	2.5
10	1.85	2	2.16	2.34	2.52
11	1.87	2.03	2.19	2.36	2.55
12	1.9	2.05	2.22	2.39	2.58
13	1.91	2.06	2.23	2.41	2.6
14	1.94	2.09	2.25	2.44	2.64
15	1.95	2.12	2.28	2.46	2.66
16	1.97	2.13	2.3	2.48	2.68
17	1.99	2.15	2.33	2.51	2.71
18	2.02	2.18	2.35	2.55	2.75
19	2.03	2.19	2.36	2.55	2.76
20	2.05	2.22	2.39	2.58	2.79
21	2.07	2.25	2.42	2.62	2.83
22	2.09	2.25	2.44	2.63	2.85
23	2.11	2.28	2.46	2.66	2.87
24	2.14	2.31	2.49	2.69	2.91
25	2.15	2.33	2.52	2.72	2.94

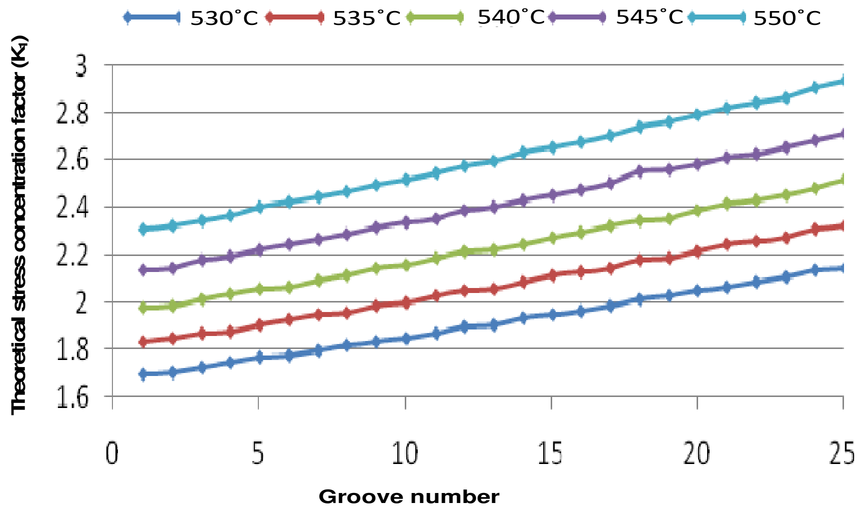

Figure 6. Variation of theoretical stress concentration factor with respect to groove.

Table 4. Groove number Vs dynamic stresses.

Groove no.	Dynamic stresses (N/m^2) ×10^7					
	Operating	530℃	535℃	540℃	545℃	550℃
1	1.2937470	2.1037452	2.2724947	2.4524943	2.6437439	2.8574934
2	1.4178348	2.2978702	2.4812108	2.6767743	2.8967831	3.1290147
3	1.5348290	2.5055756	2.7023485	2.9122397	3.1483672	3.3976130
4	1.6444978	2.6757931	2.8848394	3.1217586	3.3726142	3.6374062
5	1.7612870	2.8620914	3.0822522	3.3317679	3.5959609	3.8895088
6	1.8409324	3.0068563	3.2523139	3.4977715	3.7892525	4.0960745
7	1.9431621	3.1536566	3.4084975	3.6792660	3.9818896	4.3004407
8	2.0217210	3.2873512	3.5503393	38297641	4.1420625	4.4707976
9	2.0917185	3.4074770	3.6942449	3.9810127	4.3015180	4.6388920
10	2.1529227	3.5135699	37891440	4.0991648	4.4264091	4.7708767
11	2.2226027	3.6051667	3.9026804	4.2176949	4.5502103	4.9177273
12	2.2657251	3.6995044	4.0004209	4.3190385	4.6553571	5.0270776
13	2.2992820	3.7430173	4.0460234	4.3668535	4.7233313	5.0976330
14	2.3409107	3.8062136	4.1099959	4.4316477	4.7890387	5.1821687
15	2.3546089	3.8351585	41562415	4.4773246	4.8340835	5.2265183
16	2.3579686	3.8472120	4.1486064	4.4854591	4.8400408	5.2300807
17	2.3683014	3.8419112	4.1576847	4.4910012	4.8418607	5.2278061
18	2.3500257	3.8360715	4.1471042	44754167	4.8382883	5.2184395
19	2.3206392	37773908	4.0822923	4.4041328	4.7598512	5.1494476
20	2.2964311	3.7337657	4.0311452	4.3450458	4.6919887	5.0719737
21	2.2436321	3.6539153	3.9584082	4.2629011	4.6154719	4.9840686
22	2.1789498	3.5543153	3.8324791	4.1415500	4.4660744	4.8369595
23	2.1169559	3.4345020	3.7157756	4.0118536	4.3375391	4.6780286
24	2.0270842	3.3080888	3.5755513	3.8570908	4.1667842	4.5046316
25	1.9378292	3.1456543	3.3978375	3.6765664	3.9685680	4.2871153

temperature of 550℃.

Dynamic analysis

Variation of dynamic stresses with respect to grooves is shown in Table 4. These readings are plotted in Figure 7. Effect of dynamic stresses on fatigue stress concentration factor is given in Table 5 and plotted in Figure 8. The way the fatigue stress concentration factor is varying

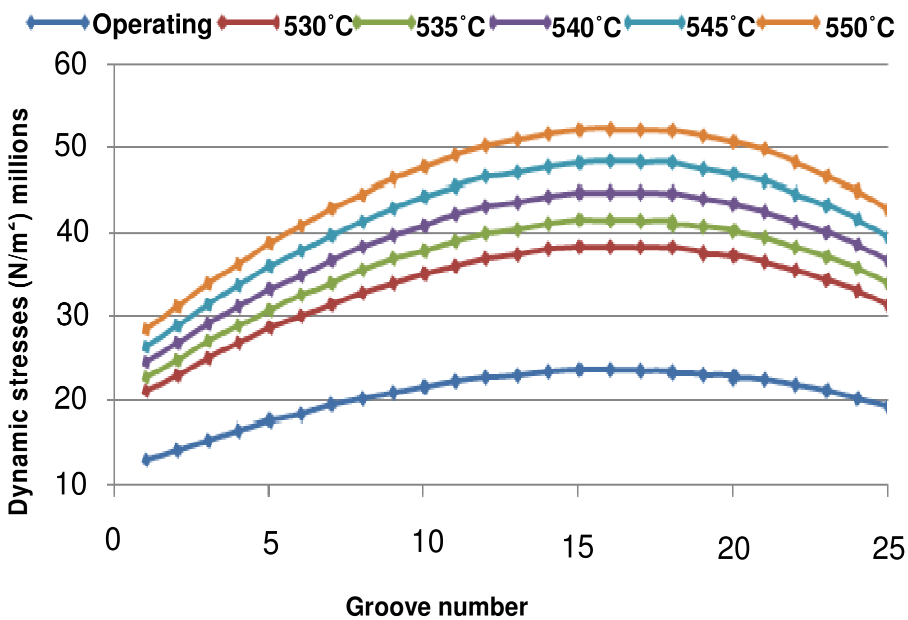

Figure 7. Variation of dynamic stress with respect to groove.

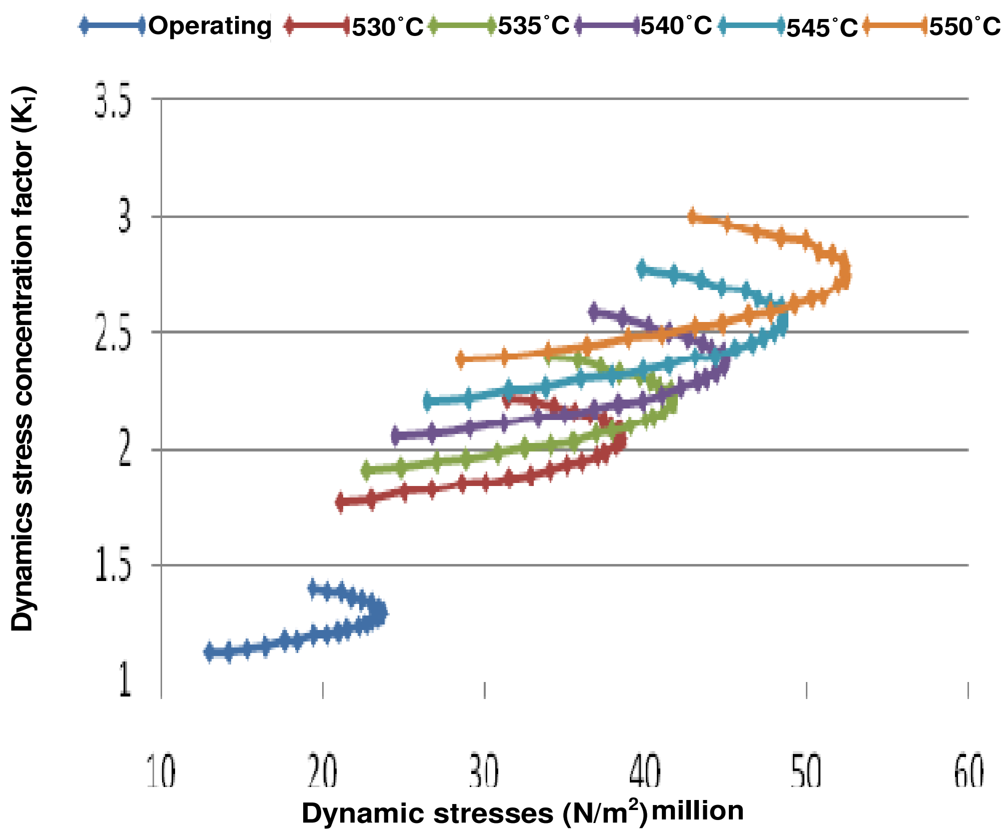

Figure 8. Dynamic stress concentration factor with respect to dynamic stress.

Table 5. Dynamic stress vs. fatigue stress concentration factor.

Groove No.	Dynamic stresses (N/m^2) × 10^7						Fatigue stress concentration factor (K_f)					
	Operating	530°C	535°C	540°C	545°C	550°C	Operating	530°C	535°C	540°C	545°C	550°C
1	1.2937470	2.1037452	2.2724947	2.4524943	2.6437439	2.8574934	1.14	1.78	1.92	2.06	2.22	2.39
2	1.4178348	2.2978702	2.4812108	2.6767743	2.8967831	3.1290147	1.14	1.79	1.93	2.07	2.23	2.4
3	1.5348290	2.5055756	2.7023485	2.9122397	3.1483672	3.3976130	1.15	1.82	1.95	2.1	2.26	2.43
4	1.6444978	2.6757931	2.8848394	3.1217586	3.3726142	3.6374062	1.16	1.83	1.96	2.12	2.28	2.45
5	1.7612870	2.8620914	3.0822522	3.3317679	3.5959609	3.8895088	1.18	1.86	1.99	2.14	2.31	2.49
6	1.8409324	3.0068563	3.2523139	3.4977715	3.7892525	4.0960745	1.18	1.86	2.01	2.15	2.32	2.5
7	1.9431621	3.1536566	3.4084975	3.6792660	3.9818896	4.3004407	1.2	1.88	2.03	2.18	2.35	2.53
8	2.0217210	3.2873512	3.5503393	3.8297641	4.1420625	4.4707976	1.21	1.9	2.04	2.2	2.37	2.55
9	2.0917185	3.4074770	3.6942449	3.9810127	4.3015180	4.6388920	1.22	1.92	2.07	2.22	2.4	2.58
10	2.1529227	3.5135699	3.7891440	4.0991648	4.4264091	4.7708767	1.23	1.94	2.08	2.24	2.41	2.59
11	2.2226027	3.6051667	3.9026804	4.2176949	4.5502103	4.9177273	1.24	1.95	2.11	2.27	2.44	2.63
12	2.2657251	3.6995044	4.0004209	4.3190385	4.6553571	5.0270776	1.25	1.98	2.13	2.3	2.47	2.66
13	2.2992820	3.7430173	4.0460234	4.3668535	4.7233313	5.0976330	1.26	1.99	2.14	2.31	2.49	2.67
14	2.3409107	3.8062136	4.1099959	4.4316477	4.7890387	5.1821687	1.28	2.02	2.17	2.33	2.51	2.71
15	2.3546089	3.8351585	4.1562415	4.4773246	4.8340835	5.2265183	1.29	2.04	2.2	2.36	2.54	2.74
16	2.3579686	3.8472120	4.1486064	4.4854591	4.8400408	5.2300807	1.3	2.05	2.21	2.38	2.56	2.76
17	2.3683014	3.8419112	4.1576847	4.4910012	4.8418607	5.2278061	1.32	2.07	2.23	2.4	2.58	2.78
18	2.3500257	3.8360715	4.1471042	4.4754167	4.8382883	5.2184395	1.32	2.1	2.26	2.43	2.62	2.82
19	2.3206392	3.7773908	4.0822923	4.4041328	4.7598512	5.1494476	1.33	2.11	2.27	2.44	2.63	2.84
20	2.2964311	3.7337657	4.0311452	4.3450458	4.6919887	5.0719737	1.35	2.13	2.3	2.47	2.66	2.86
21	2.2436321	3.6539153	3.9584082	4.2629011	4.6154719	4.9840686	1.36	2.15	2.32	2.49	2.69	2.9
22	2.1789498	3.5543153	3.8324791	4.1415500	4.4660744	4.8369595	1.37	2.17	2.33	2.51	2.7	2.92
23	2.1169559	3.4345020	3.7157756	4.0118536	4.3375391	4.6780286	1.39	2.19	2.36	2.54	2.74	2.94
24	2.0270842	3.3080888	3.5755513	3.8570908	4.1667842	4.5046316	1.4	2.22	2.39	2.57	2.76	2.98
25	1.9378292	3.1456543	3.3978375	3.6765664	3.9685680	4.2871153	1.41	2.23	2.4	2.59	2.79	3.01

with respect to dynamic stresses is shown in the Table 6. These readings are plotted in Figure 9. The dynamic stresses are obtained by considering self weight of rotor, blade weight and steam load as uniformly distributed load over a span of 1.712 m at the operating and also elevated temperatures of 530, 535, 540, 545 and 550°C.

It is observed that dynamic stresses are increasing increasing from 1.2937470 × 10^7 to 23683014 N/m^2 from the 1st to 17th groove and gradually decreasing to a value of 1.9378292 × 10^7 N/m^2 to a last groove of 25th at the operating temperature. It is observed that the dynamic stresses increased from 2.1037452 × 10^7 to 3.8472120 × 10^7 N/m^2 from the 1st to 16th groove and gradually decreasing to 25th groove to a value of 3.1456543 × 10^7 N/m^2 at the temperature of 530°C. At the temperature 535°C, dynamic stresses are 2.2724947 × 10^7 N/m^2 at the 1st groove and gradually increasing to 4.1576847 × 10^7 N/m^2 up to 17th groove and gradually decreasing to 3.3978375 × 10^7 N/m^2 to the last groove of 25th groove. It is observed that dynamic stresses increased from 2.4524943 × 10^7 to 4.4910012 ×

Table 6. Groove number vs. fatigue stress concentration factor.

Groove no.	Fatigue stress concentration factor (K_f)					
	Operating	530°C	530°C	535°C	540°C	545°C
1	1.14	1.78	1.92	2.06	2.22	2.39
2	1.14	1.79	1.93	2.07	2.23	2.4
3	1.15	1.82	1.95	2.1	2.26	2.43
4	1.16	1.83	1.96	2.12	2.28	2.45
5	1.18	1.86	1.99	2.14	2.31	2.49
6	1.18	1.86	2.01	2.15	2.32	2.5
7	1.2	1.88	2.03	2.18	2.35	2.53
8	1.21	1.9	2.04	2.2	2.37	2.55
9	1.22	1.92	2.07	2.22	2.4	2.58
10	1.23	1.94	2.08	2.24	2.41	2.59
11	1.24	1.95	2.11	2.27	2.44	2.63
12	1.25	1.98	2.13	2.3	2.47	2.66
13	1.26	1.99	2.14	2.31	2.49	2.67
14	1.28	2.02	2.17	2.33	2.51	2.71
15	1.29	2.04	2.2	2.36	2.54	2.74
16	1.3	2.05	2.21	2.38	2.56	2.76
17	1.32	2.07	2.23	2.4	2.58	2.78
18	1.32	2.1	2.26	2.43	2.62	2.82
19	1.33	2.11	2.27	2.44	2.63	2.84
20	1.35	2.13	2.3	2.47	2.66	2.86
21	1.36	2.15	2.32	2.49	2.69	2.9
22	1.37	2.17	2.33	2.51	2.7	2.92
23	1.39	2.19	2.36	2.54	2.74	2.94
24	1.4	2.22	2.39	2.57	2.76	2.98
25	1.41	2.23	2.4	2.59	2.79	3.01

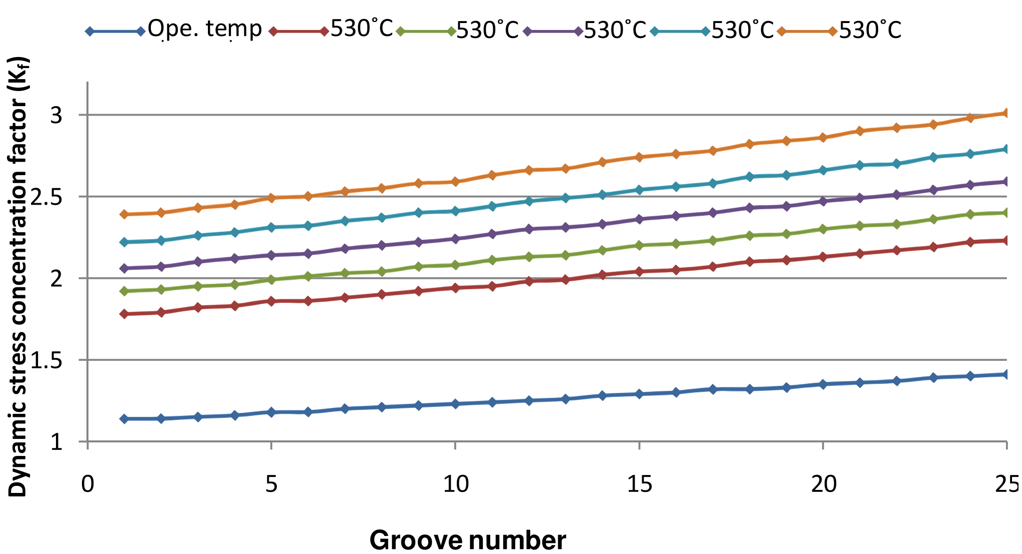

Figure 9. Variation of dynamic stress concentration factor with respect to groove.

10^7 N/m^2 from the 1st to the 17th groove and gradually decreasing to 3.6765664 × 10^7 N/m^2 at the temperature of 540℃.At the temperature of 545℃, dynamic stresses were 2.6437439 × 10^7 N/m^2 at the 1st groove and gradually increasing to 4.8418607 × 10^7 N/m^2 up to 17th groove and gradually decreasing to 3.9685680 × 10^7 N/m^2 to 25th groove. It is observed that the dynamic stresses increased from 2.8574934 ×10^7 to 5.2300807 × 10^7 N/m^2 from the 1st to the 16th groove and gradually decreasing to the 25th groove to a value of 4.2871153 × 10^7 N/m^2 at the temperature of 550℃.

Conclusion

In this study, an attempt was made to compute stress concentration factors due to thermal and fatigue loadings. The methodology adopted gives a systematic theoretical investigation to predict high concentration of stress and its impact on the life of the rotor. At the end of the analysis, it is concluded that at 545℃ there will be a high concentration of stress and hence it is suggested to operate the turbine corresponding to inlet steam temperature which is less than 545℃.

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