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Research Article

Balance Cut Analysis for Stress and Balance Capacity of a Turbocharger Turbine Wheel

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Abstract

Turbochargers are used to increase the output power of the engine and make use of the exhaust gases to rotate the impeller which is coupled to the turbine wheel by a shaft. The turbine wheels being manufactured by the process of casting are subjected to possess unbalance in them, which is mainly with respect to the mass distribution. The uneven distribution of material across the wheel back face acts as a stress raiser which may lead to wheel burst in critical conditions. Balancing machines with grinding units are used to balance the turbine wheel with the right amount of material being removed in the units of gram millimeter which is termed as the balance capacity. To achieve maximum material removal, higher values of balance capacity need to be achieved without compromising the stress values of the wheel. Various parameters are considered for achieving the target. The tool used for obtaining the optimum value of the parameters is the design of experiments. The response surface optimization is used in which the design of experiments generates design points for each parameter and gives the optimum value of the parameters to achieve the expected balance capacity and also ensure that the stress is within the acceptable range.

Keywords: *Balancing, turbine wheel, imbalance, stress analysis, balance capacity, design of experiments, response surface optimization*

1. Introduction

Turbochargers boost the engine power by employing the energy of the exhaust gases to rotate the turbine wheel. The wheel being manufactured by casting process is made up of material Inconel, known for its properties like high temperature and pressures resistance in addition to corrosion and oxidation resistance. The casting process causes defects in the wheel and unbalance is one of it. Uneven mass distribution causes high stresses in the critical regions of the wheel, affecting the turbo performance and safety included.

The parameters considered are the depth of cut, grinding wheel diameter, tip radius and groove location. Since the value of these input parameters can be altered, they are termed as controllable. The output parameters, also termed as fixed parameters are the groove stress and balance capacity. Response surface optimization is used to obtain optimum values of these parameters by generating design points for each parameter.

The design of experiment helps to achieve a relation between the input and output parameters by generating number of design points over a random range of the parametric values. The DoE type optimum space filling is preferred over the other types due its advantages of generating maximum design points for good variation and the percentage of accuracy which helps achieve optimum values. The response surface optimization generates responses between the input and output parameters by using the data generated from the DoE in 2D and 3D forms. The combinations of RSM with the used DoE are best utilized with Standard response and Kriging types of RSMs.

The optimization tool allows us to set various objectives for optimization using minimize, maximize and seek target options where we can define the limits for each parameter. The type of optimization needs to be selected for multiple variables. The optimum values are highlighted in the chart which can be used as input for the next analysis with optimized values and minimum errors.

2. Methodology

The balance groove is created on the back face of the turbine wheel using a grinding wheel on a balancing machine. This is replicated analytically in ANSYS Workbench software by generating a grinding wheel profile and then moving it through various planes

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(base plane, grinding wheel plane, align cutter plane, set groove radius plane, depth of cut plane) to create the groove on the wheel by material removal.

The next step after profile creation is the meshing of the critical locations in order to minimize the stress values. The critical locations include the groove, back face, internal machining radius, external machining radius, pressure root radius and suction root radius. The following figure 1, shows the critical locations of the turbine wheel.

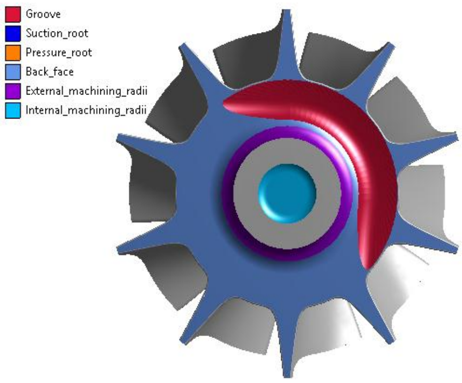


Figure 1 Turbine Wheel: Critical locations

The structural analysis of turbine wheel is done by applying boundary conditions and the load. The boundary conditions include displacement on the shaft end of the wheel and cylindrical supports. The load applied is the rotational force in RPM. The rotational speed range is between 75,000-1,25,000 RPM. Figure 2(a) shows the boundary conditions applied, whereas 2(b) shows the direction of rotational load applied.

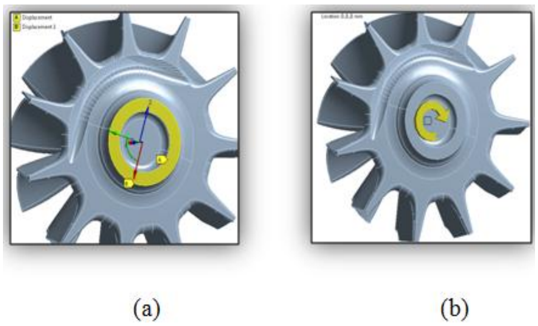


Figure 2 Boundary conditions and loads applied

After applying the structural boundary conditions and the load, the stress analysis is done which shows the stress variations across the turbine wheel. The stress value is found to be highest at the groove location due to the material discontinuity. The high stress region is indicated in red color and the low stress region in dark blue. The stress variation helps in understanding the placement of groove on the wheel back face. The centrifugal forces act on the wheel creating high stresses. The area of wheel at the centre being minimum, the stresses are highest at that location. Thus placing a groove near to the centre would act as a stress raiser and it is recommended to create a groove away from centre towards the edge of the wheel. But care also needs to be taken so to avoid exceeding the groove outer limits.

Figure 3 shows the stress plot of a turbine wheel after structural analysis and the variation in stresses across the turbine wheel.

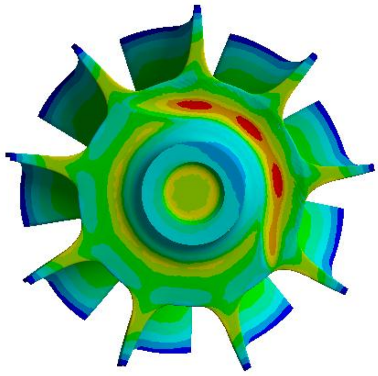


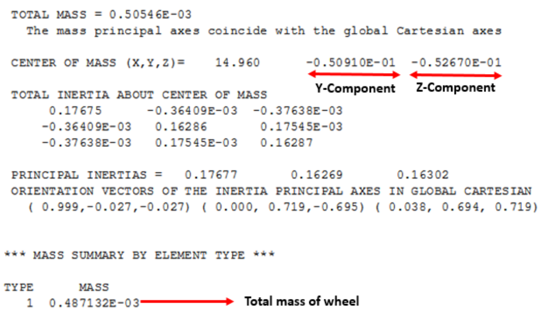
Figure 3 Stress plot of turbine wheel

The balance capacity needs to be calculated from the mass components of the solution. Individual masses in the y and z component are needed along with the total mass of the wheel excluding the shaft.

3. Calculations

The balance capacity of the wheel is calculated to determine the amount of material to be removed in order to balance the wheel and also the effect of variation in different parameters on the balance capacity. the unit used for measuring the balance capacity is gram millimeter (gmm).

The Y-Component, Z-Component and total mass are obtained after the completion of analysis.



```
TOTAL MASS = 0.50546E-03
  The mass principal axes coincide with the global Cartesian axes

CENTER OF MASS (X,Y,Z)=    14.960      -0.50910E-01  -0.52670E-01

TOTAL INERTIA ABOUT CENTER OF MASS
     0.17675      -0.36409E-03  -0.37638E-03
    -0.36409E-03   0.16286       0.17545E-03
    -0.37638E-03   0.17545E-03   0.16287

PRINCIPAL INERTIAS =   0.17677       0.16269       0.16302
ORIENTATION VECTORS OF THE INERTIA PRINCIPAL AXES IN GLOBAL CARTESIAN
  ( 0.999,-0.027,-0.027) ( 0.000, 0.719,-0.695) ( 0.038, 0.694, 0.719)

*** MASS SUMMARY BY ELEMENT TYPE ***

TYPE      MASS
   1   0.487132E-03
```


Figure 4 Mass components for calculating balance capacity

Figure 4 shows the mass components for balance capacity. The balance capacity is calculated by using the formula:

$BC = (YC^2 + ZC^2) * \text{Total mass} * 1000000$

Substituting the values,

$BC = [(-0.50910E-01)^2 + (-0.52670E-01)^2]*505$

BC = 2.70 gmm (gram millimeter)

4. Analysis and Discussion

Response surface optimization of the turbine wheel is carried out after the structural stress analysis and determination of the balance capacity. The first step in RSM is the design of experiments.

i) Design of experiments

The DoE tool generates design points for each parameter selected and the values are taken randomly between the range of the lowest and the highest limits specified. The values for limits are obtained through previous test results data.

Optimum space filling type DoE is used as it gives more variation in the design points so an optimum value can be obtained. The following Figure 5 shows chart of design points for the parameters grinding wheel diameter and the cutter tip radius.

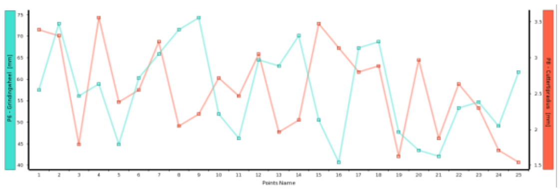


Figure 5 DoE Chart: optimum Space Filling

The following table shows design points for depth of cut and radius. The design points for depth of cut are obtained in the range of 1.111 and 1.2889 with the random intermediate values. Similarly for the wheel radius random design points are obtained between 19.278 and 23.722. The DoE is run for every design points having random values to achieve the optimum value point for which the response will be generated.

Table 1 Design points generated in DoE

Table of Schematic E2: Design of Experiments (Optimal Space-Filling Design : Max-

	A	B	C
1	Name	P1 - CutDepth.FD1 (mm)	P4 - Radius.FD1 (mm)
2	1	1.2444	19.833
3	2	1.2889	20.944
4	3	1.1556	22.611
5	4	1.2222	22.056
6	5	1.1333	19.278
7	6	1.1778	20.389
8	7	1.2	23.722
9	8	1.2667	23.167
10	9	1.1111	21.5

ii) Response Surface

The response surface method generates response for the design of experiments selected and gives the output as a function of the input provided. The types of RSM used for optimum results can be either Standard response method or Kriging.

The main effect of the input parameters on the output parameters can be understood from the graphs below. The main effect plot for tip radius as input parameter on the groove stress in Fig 6 shows that increase in tip radius leads to decreasing groove stress value. Larger tip radius increases groove area, thus minimizing the stress values.

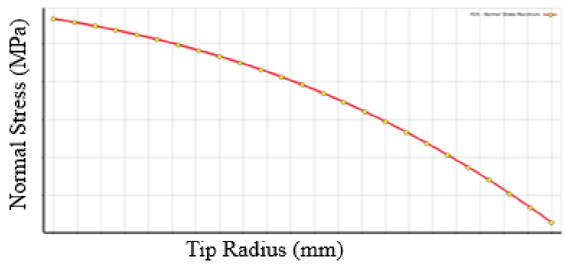


Figure 6 Main effect plot for normal groove stress

The main effect plot for input parameter (depth of cut) on the balance capacity which is an output parameter is represented in fig.7. Increase in depth of cut removes more material achieving higher balance capacity values.

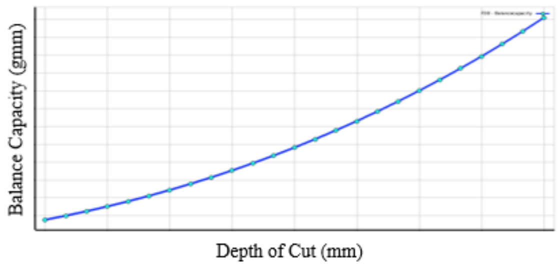


Figure 7 Main effect plot for balance capacity

The 3D response chart shows a combined response of various input parameters on the output parameter in the form of a 3D curve which is generated based on an equation. Fig 8 shows 3D response for tip radius and depth of cut on the output parameter (normal groove stress). The range of values can also be understood through the 3d response charts.

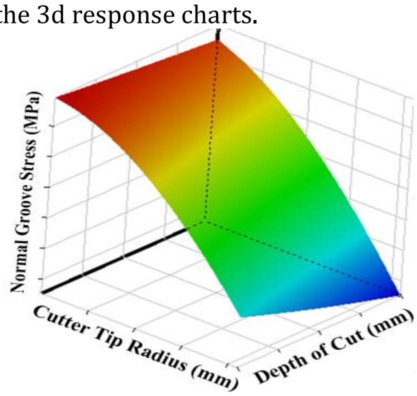


Figure 8.3D response chart for normal groove stress

iii) Optimization

The objectives of optimization are defined wherein the stress is to be minimized seeking the target of the safe limit and the balance capacity to be maximized. The method of optimization can be either set to Screening or Multi Objective Genetic Algorithm (MOGA).

Candidate points are obtained highlighting the effect for each parameter. The yellow stars indicate optimum results, the dash indicates a possibility with lower impact and Red Cross indicates impossibility of existence. This helps in selecting optimum value of the parameters.

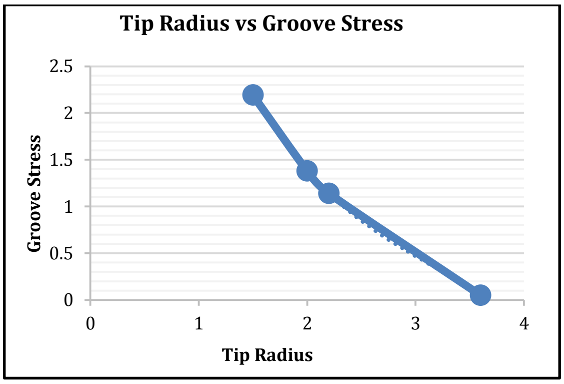
Table 2 Candidate points for optimization

Candidate Points	Candidate Point 1	Candidate Point 2	Candidate Point 3	Candidate Point 4	Candidate Point 5
P6 - Grindingwheel (mm)	★ 40.984	★★★ 47.764	★★ 53.164	★★ 53.164	★ 40.889
P8 - Cuttertipradius (mm)	★★ 2.3214	– 3.589	★ 3.312	★ 3.312	★ 1.9228
P41 - set_groove.FD1 (mm)	18.022	18.036	18.3	18.301	18.168
P42 - depth_cut.FD1 (mm)	0.63289	0.72409	0.73411	0.73411	0.64181
P43 - gwplane.FD1 (mm)	-50.649	-50.096	-49.385	-49.388	-49.891
P23 - Cutinnerradius (mm)	★ 16.829	★ 16.274	★ 16.62	★ 16.621	– 17.134
P25 - Cutouterradius (mm)	– 20.329	– 20.94	✗ 21.302	✗ 21.303	– 20.406

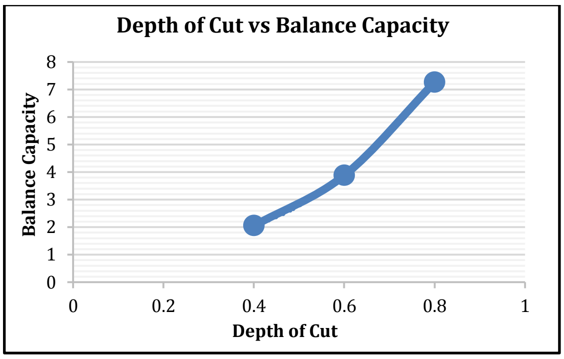
5. Results

The behaviour of the output parameters with respect to the input parameters is determined by using response surface optimization. The effect of the two critical input parameters, tip radius and depth of cut is shown graphically on the output parameters, groove stress and balance capacity respectively.

The increase in value of tip radius increases the groove area thus minimizing the groove stress value. The analysis is performed for four different tip radii.



Graph 1 Tip radius vs groove stress



Graph 2 Depth of cut vs Balance capacity

The graph 2, shows the effect of depth of cut on the balance capacity of the turbine wheel, again obtained through response surface optimization. Increase in the depth of cut value, removes more material from the turbine wheel back face thus increasing the balance capacity which is desired to achieve optimum balancing of the turbine wheel.

The variation in the values of parameters needs to be within the acceptable limits which are achieved by the previous data of the organization based on various tests. Thus it is mandatory to maintain the values of parameters within these acceptable limits for the safe and efficient operation of the component. The following fig 9 shows percent variation of the parameters from the acceptable limits.

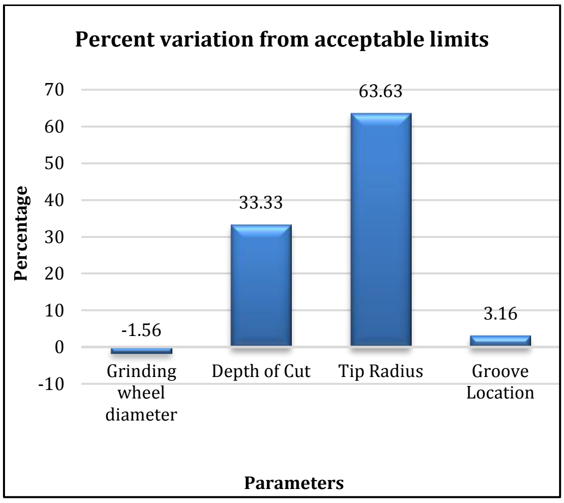


Figure 9 Percent variation of parameters from acceptable limits

The analysis is carried out for all the critical parameter and a correlation is obtained in order to understand the relation and variation between the parameters. This helps in reducing the iteration time and increasing accuracy. Fig 10 shows the parametric co-relation.

S.N	Constant Parameter	Parameter	Variations	Groove Stress	Balance Capacity
1	Depth of Cut	Grinding wheel diameter	↑	↓	↑
			↓	↑	↓
2	Depth of Cut	Tip Radius	↑	↓	↑
			↓	↑	↓
3	Grinding Wheel Diameter	Depth of Cut	↑	↑	↑
			↓	↓	↓
4	Depth of Cut / Grinding Wheel Diameter	Groove Location	↑	↓	↑
			↓	↑	↓

Figure 10 Parametric Co-relation

Conclusions

The intent of the paper was to understand the effect of the critical input parameters and their variation on the output parameters. The tool used for analysis is response surface optimization. The balancing of turbine wheel is carried out by material removal process which involves creation of a balance groove on the back face of the turbine wheel.

The objective of the process was to achieve maximum material removal (balance capacity) and minimizing the groove stress value within the acceptable limits to ensure safety and efficient functioning of the turbocharger. The parameters like depth of cut, tip radius, grinding wheel diameter and groove location play important role in achievement of the stated output parameters required for good results. The variation in these parameters leads to change in the output parameters. To study this variation response surface optimization is used.

The design points are generated for each parameter in design of experiments which have a range of minimum and maximum values with random points. Responses are generated for each of these design points and one with minimum errors and good variations are selected for optimization. The candidate points generated in the optimization process highlight the optimum value of parameters which is selected as the final input for the analysis.

The response surface optimization process used for this analysis suggests effective methods for obtaining optimum results with minimum errors. The time required for iterations is also greatly reduced. Another outcome is the co-relation between various parameters and the effect of variation in them which is highlighted through main effect plots and 3D responses. The percentage variation of parameters from acceptable limits is also highlighted. This helps in efficient balancing of the turbine wheel assuring its safety.

References

Lei Fu, Yan Shi, Qinghua Deng, Huaizhi Li and Zhenping Feng (January 2012), Integrated Optimization Design for a Radial Turbine Wheel of a 100 kW-Class Microturbine, *Journal of Engineering for Gas Turbines and Power*, vol. 134, pp. 1-8.

F. Seve, M.A. Andrianoely, A. Berlioz, R. Dufour, M. Charreyron (30 May 2002), Balancing of machinery with a flexible variable-speed rotor, *Journal of Sound and Vibration* , pp.287–302.

Lasse Mueller, Zuheyr Alsalihi and Tom Verstraete (March 2013), Multidisciplinary Optimization of a Turbocharger Radial Turbine, *Journal of Turbomachinery*, Vol. 135.

Geng Zhi, Xuekun Li, Weiyao Bi, Jiajun Tang and Yiming Rong (8 April 2015), The measurement and analysis of micro bonding force for electroplated CBN grinding wheels based on response surface methodology, *Engineering Failure Analysis*, pp.377-388.

Warren C. Young and Richard G. Budynas, Roark's formulas for stress and strain, 7th edition, McGraw-Hill. ISBN 0-07-072542-X.

VulloVincenzo and VivioFrancesco, Rotors: Stress Analysis and Design, MechanicalEngineering Series, Springer-Verlag Mailand Publishers.