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Compressor Cover Optimization by using Response Surface Methodology and Computational Fluid Dynamics

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ABSTRACT

Turbocharger is playing an important role in achieving new regulations, fuel efficiency targets and space claim targets in automotive and power generation market segment. Turbocharger is a system having a turbine and compressor which uses exhaust gas energy to increase the density of air at the inlet of engine. With growing demand for better performing turbocharging system, need to improve efficiency at component level that is compressor and turbine. The conventional methods to improve the compressor performance are improvement in the impeller performance or reduction in the losses in compressor cover. In this work, an investigation has been carried out on the effect of compressor cover geometrical parameters like diffuser width, critical area, and diffuser radius ratio on compressor stage performance by using response surface methodology and simulation will be done in CFD, to predict the compressor stage performance for arriving at optimum cover sizing parameters.

Keywords — Turbocharger, Compressor Cover, Optimization, Computational Fluid Dynamics, Response Surface Methodology, Compressor Stage Efficiency, Design of Experiments.

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I. INTRODUCTION

Instead of the conventional one factor at a time experiments, DOE method is used to get effect of various parameters and study their interaction effects on compressor cover performance. DOE helps in minimizing experimental error and improves the robustness of the design or process to variation and determines the levels at which to set the controllable factors. The aerodynamic performance of the compressor cover by varying the geometrical parameters has been observed. It has further been concluded that the performance of compressor stage is strongly dependent on the chosen set of parameters. At different speed lines, the effect of geometrical parameters on peak efficiency of compressor cover is observed with the help of RSM. By careful design of *experiments*, the objective is to understand effect on response (output variable) which is influenced by several *independent variables* (input variables). An experiment is a series of tests, called *runs*, in which changes are made in the input variables in order to identify the reasons for changes in the output response. The response surface methodology analysis, has been used for optimization. RSM is used for the approximation of both experimental and numerical responses. An investigation will be carried out to study the effect of compressor cover geometrical parameters on aerodynamic performance of compressor stage, Diffuser width**,** Critical area**,** Diffuser radius ratio on compressor stage performance. By using response surface methodology, simulation will be done in CFD, to predict the compressor stage performance for arriving at optimum cover sizing parameters.

I. LITERATURE REVIEW

Due to increased focus on fuel economy, efforts are being made to improve the overall turbocharger efficiency, which in turn require improvement in compressor stage efficiency and operating range of compressor as it plays an important role in placing the engine running line in efficient zone. Further to this improvement in low end performance is required in order to meet low end torque requirements. Several works on improving the operating range of compressor has been done previously. Bahram Nikpour et al. [2], a compressor typically for use in a turbocharger comprises a downstream radial compressor impeller wheel, an upstream axial compressor impeller wheel and an intermediate stator. The compressor housing has an inlet with inner and outer walls that define between them an MWE gas flow passage. The position of the slot can be at one of several positions along the gas flow passage, there are second and third slots and the flow passage is divided into two parts. All the arrangements are designed to improve the compressor map width. Qingbin Li et al. [12] used DOE in conjunction with reverse engineering to optimize the compressor stage parameters inlet diameter, exducer and diffuser widths in order to meet specific application requirements. Results shows improvement in pressure ratio by 0.2 percent and in peak efficiency by 2 percent compared to baseline.

Objective of current analysis is to understand effect of chosen set of geometrical parameters on the compressor stage performance. Therefore DOE approach is followed in current work in order to systematically understand the performance of compressor stage with diffuser radius ratio, diffuser gap and area schedule

II. THEORY

A forced induction compressor driven by a turbine powered by the exhaust gas of the engine is known as a turbocharger. Rather than using engines shaft work to power the compressor, the exhaust gas collected from the cylinders is directed to a turbine connected to the compressor at the air intake. As a result, the efficiency of the engine is high, and the fuel consumption stays low. Thermal efficiency, or fraction of energy in the fuel-air mixture that is converted to output power or shaft work, is always greater with a turbocharger than with a mechanically driven supercharger.

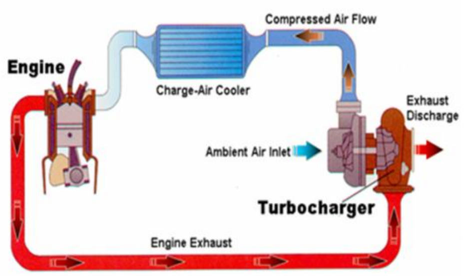

Figure 1: Schematic Layout of Turbocharger

As shown in the given Figure 1, heat and exhaust energy of engine exhaust gas is utilized by turbine assembly to rotate the turbine wheel. Turbine casing, due to its geometry, act as a nozzle, which increases the velocity of the air and focuses on turbine blade, thus kinetic energy converted to rotational energy. As turbine wheel rotates, compressor wheel also rotates as it is coupled with turbine wheel via bearings. This compressor wheel compresses the entering air to higher pressure and temperature along with high velocity. This compressed air is passing through diffuser to reduce the velocity of air, which in turns increases more air pressure. This compressed air then passes through the compressor housing volute to engine intake manifold, which is further supplied in cylinder. Entering air in compressor is at atmospheric condition, which on compression, becomes denser and lighter with high temperature up to 200ºC, thus combustion of fuel is complete and cleaner. The amount of air pressure rise and delivery air volume from the compressor outlet is decided from wheel size, housing size and design and turbocharger matching.

III. CFD ANALYSIS OF A COMPRESSOR COVER

Introduction to Sensitivity Analysis: Sensitivity analysis is a technique used to determine how different values of an independent variable will impact a particular dependent variable under a given set of assumptions. It is the reverse engineering approach used in the compressor cover design, to determine effect of various key design parameters on compressor stage performance. This approach also evaluates the significance of key design parameters in the design and is sometimes followed by Design of Experiments to work out best combination of parameters that leads to optimum performance out of all possible combinations.

Selection of Key Design Parameters

The key design parameters are the parameters which causes considerable effect on the performance of the compressor cover due to change in that parameter. Generally the geometric parameters are the key design parameters which give the major contribution in effect on the performance parameter. The main geometric parameters considered for sensitivity analysis are, Area schedule, Diffuser radius ratio, Diffuser width

DOE on Key Design Parameters: Design of experiments (DOE) is systematic series of experiments in which various input variables (X's) are directly varied and the effects on the output variables (Y's) are observed. It also helps us to determine which X's most affect the Y's.Variable X's refers to factors which are varied in a systematic manner during experiments. Levels refer to value of factors. Variable Y's refers to Response which is measured and required to be optimized. Main Effect refers to response change due to change in level of factor. Interaction Effect refers to response change due to change in level of factor depends on level of another factor.

Table 1: shows the factors with 3 levels selected for DOE in coded unit

Factors	Low Level	Mid-Level	High Level
Area schedule	-1	0	1
Diffuser radius Ratio	-1	0	1
Diffuser width	-1	0	1

Table 1: Factors with 3 levels selected for DOE

Based on above factors and levels, DOE is designed and analyzed using Response Surface Method available in Minitab tool shows that total 20 number of runs to be performed in the sequence shown in Run Order Column. For each experiments 3 response were recorded i.e. Peak Efficiency at non-dimensional speeds of 0.28, 0.448 and 0.636 respectively using CFD analysis. Results shown are normalized with respect to reference efficiency.

Fluid cavity extraction: To extract fluid volume inside centrifugal compressor. Using Creo Parametric software 2.0 version, Fluid cavity is created for different geometries. Creosoftware is a feature based, parametric solid modelling program. Fluid cavity is volume occupied by fluid inside a component / system.

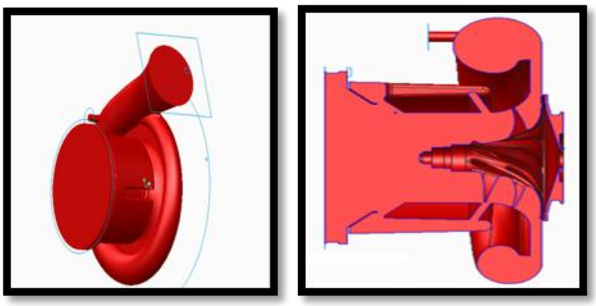

Figure 2: Cross section view of extracted fluid cavity

We obtained the cavities for all the concepts generated in DOE by increasing or decreasing the area, diffuser radius ratio and diffuser width. There are total 15 stage cavities created for DOE.

CFD analysis for Baseline model and DoE concepts:

ANSYS CFX-Pre-Processing: It is used to define the simulation. The first step is importing the generated meshes in CFX- Pre. Secondly is to specify the physics characters of materials, boundary conditions, initial values and solver parameters. The meshing for impeller, diffuser, and compressor cover (scroll) modeled in Creo_2.0 is performed in ICEM. Then shell meshing parameters are also fixed and volume mesh parameter is set where the type of mesh selected is TETRA / MIXED with Robust (octree) method. Then Prism meshing is also applied to capture the boundary layer physics as deep as possible with suitable meshing parameters. In this way we specified global meshing parameters

In the figure 3, inlet and outlet flow of air is shown. Compressor is defined with its various boundary conditions.

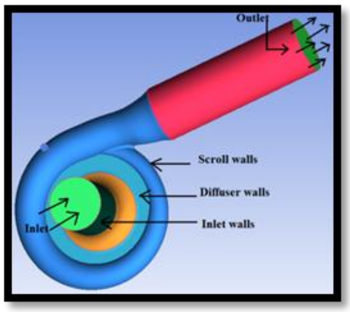

Figure 3: Boundary conditions for Compressor Scroll

The given figure 4, is the meshed modeled of compressor scroll for different stage cavities with different changes in geometrical parameters according to the DOE concepts. Global mesh parameters and part meshing parameters are defined to get fine mesh and good quality of mesh.

Figure 4: Meshed model of Compressor Scroll

ANSYS CFX-Solver: The solver is one where all the calculations are performed to solve the governing equations for given conditions. It solves all the solution variables for the simulation for the problem specification generated in CFX-Pre. The CFX Solver Manager module is used to control and manage the CFD task. The ANSYSCFX solver runs in high accuracy mode by default, achieving accurate flow predictions robustly and reliably.

ANSYS CFX-Post: The CFD post-processing tool uses an intuitive user interface to represent both graphical and quantitative results that makes it easy to convey fluid dynamic results. In our case we Post-processed the results for getting the outputs in the form of values; we plotted the line plots from the actual values obtained at specified sections (T-T Isentropic Efficiency Vs Mass Flow Parameter) for different three speed lines for all the DOE concepts. The respective plots with their significance are explained in results and outcomes.

V RESULTS AND DISCUSSIONS

The CFD analysis is performed on all the concepts obtained in DOE as discussed in earlier section, after post-processing the results we got the remarkable outcomes which are explained below. The graphs plotted from the CFD results for all the concepts of DOE are shown below.

A. Interpretation of geometric parameters from DOE for 0.28 speed line

Main effects plot for Peak efficiency: Figure 5, shows Main Effect Plots for 0.28 non-dimensional speed parameter from Minitab. It is observed that efficiency increases within the range for area schedule later attaining the maximum it drops down slightly. It can also be observed that there is large change in efficiency with change in area schedule compared to other diffuser radius ratio and diffuser gap. For diffuser radius ratio the efficiency goes on decreasing and then gradually increases while for diffuser gap efficiency increases gradually and then it decreases.

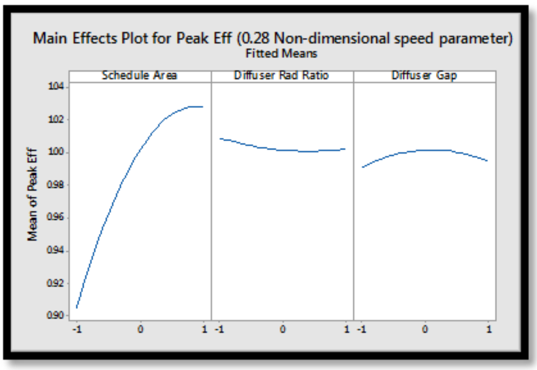

Figure 5: Main effects plot for Peak efficiency (0.28 Non-dimensional speed parameter)

Interaction plot for Peak efficiency: Figure 6 shows Interaction Plots for 0.28 non-dimensional speed parameter from Minitab. It can be seen that interaction between diffuser radius ratio / area schedule and diffuser gap/area schedule is significant.

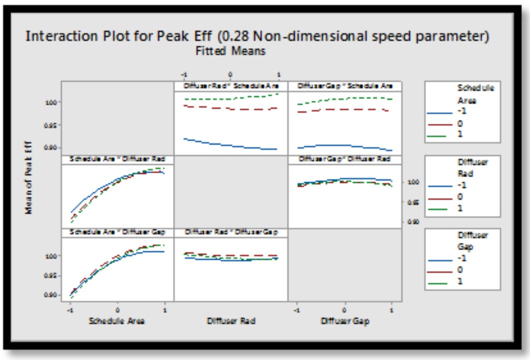

Figure 6: Interaction plot for peak efficiency (0.28 Non-dimensional speed parameter)

The effect of speed parameter on the total to total isentropic efficiency: As we have observed that at non-dimensional speed parameter 0.28, most significant parameter affecting peak efficiency is area schedule. It can be also seen clearly in figure 5.3, shown below as cavities 1,2,6,11,12 (with smallest area schedule) has lowest peak efficiencies whereas other cavities 4,5,10,14,15 (with largest area schedule) has higher peak efficiencies compared to baseline. Also point of peak efficiency is shifted towards left for cavities 1,2,6,11,12 (with smallest area schedule).

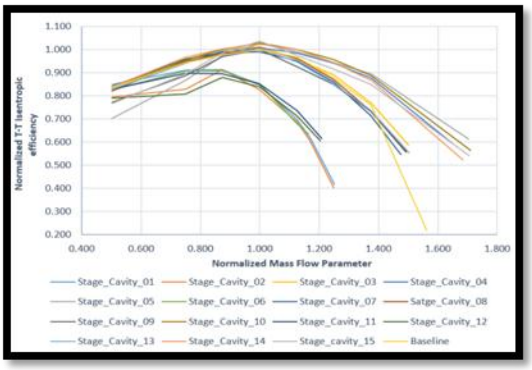

Figure 7: The graph of Normalized T-T Isentropic efficiency Vs Normalized Mass flow parameter for 0.28 non-dimensional speed parameter for all 15 stage cavities and baseline

Figure 8, shows cavities with lowest peak efficiency and highest peak efficiency compared to baseline. We can see that efficiency has marginally increased in cavity 14 at higher mass flow parameters.

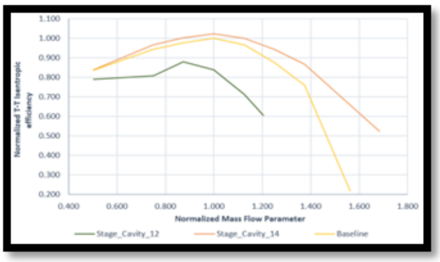

Figure 8: Normalized T-T Isentropic efficiency Vs Normalized Mass flow parameter (for 0.28 non-dimensional speed parameter)

B. Interpretation of geometric parameters from DOE for 0.448 non-dimensional speed

Main effects plot for Peak efficiency: Figure 9, shows Main Effect Plots for 0.448 non-dimensional speed parameter from Minitab. It is observed that efficiency increases within the range for area schedule later attaining the maximum it drops down. For diffuser radius ratio the efficiency goes on decreasing and then gradually increases while for diffuser gap efficiency decreases gradually.

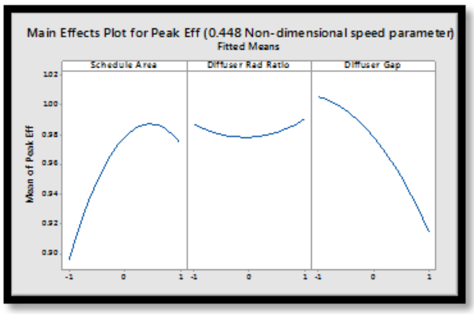

Figure 9: Main effects plot for Peak efficiency (0.448 non-dimensional speed parameter)

Interaction plot for Peak efficiency: Figure 10, shows Interaction Plots for 0.448 non-dimensional speed parameter from Minitab. Interactions can be seen between diffuser radius ratio / area schedule, diffuser gap/ area schedule, area schedule/diffuser radius and area schedule/diffuser gap.

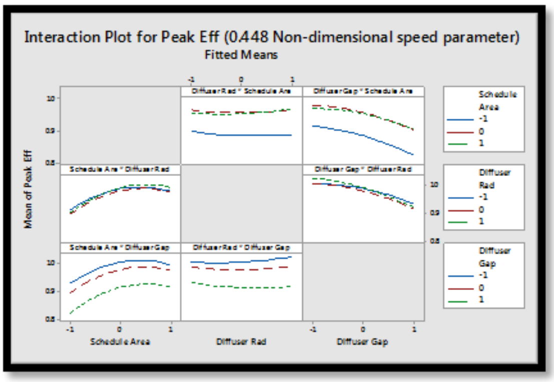

Figure 10: Interaction plot for peak efficiency (0.448 non-dimensional speed parameter)

The effect of speed parameter on the total to total isentropic efficiency: For speed line 0.448 non-dimensional speed parameter, most significant parameter affecting peak efficiency are area schedule and diffuser gap. It can be also seen verified with figure 11, shown below as cavities 1,2,5,6,9,11,12,15 (with smallest area schedule/ higher diffuser gap) has lowest peak efficiencies whereas other cavities 3,4,7,8,10,13,14 (with largest area schedule/lowest diffuser gap) has higher peak efficiencies compared to baseline.

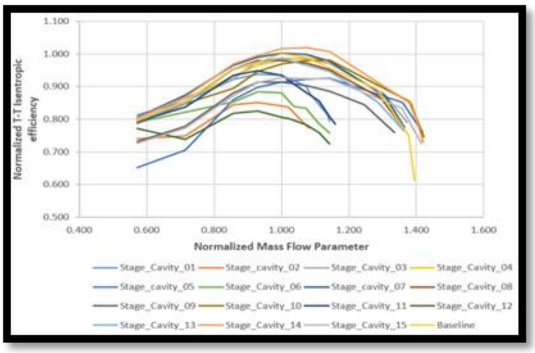

Figure 11: The graph of Normalized T-T Isentropic efficiency Vs Normalized Mass flow parameter for 0.448 non-dimensional speed parameter for all 15 stage cavities and baseline

Figure 12, shows cavities with lowest peak efficiency and highest peak efficiency compared to baseline. We can see that efficiency has marginally increased in cavity 14 at higher mass flow parameters.

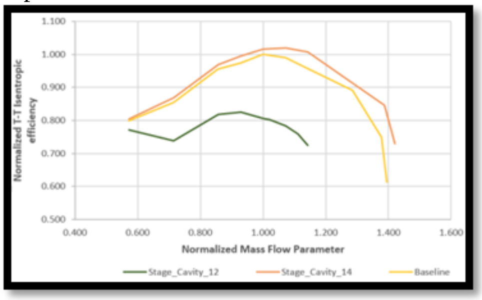

Figure 12: Normalized T-T Isentropic efficiency Vs Normalized Mass flow parameter (for 0.448 non-dimensional speed parameter)

C. *Interpretation of geometric parameters from DOE for 0.636 non-dimensional speed parameter*

Main effects plot for Peak efficiency: Figure 13, shows Main Effect Plots for 0.636 speed parameter from Minitab. It is observed that efficiency increases within the range for area schedule later attaining the maximum it drops down. For diffuser radius ratio the efficiency is almost constant, no changes are seen, it is slightly increasing for higher level while for diffuser gap efficiency decreases with increase in diffuser gap.

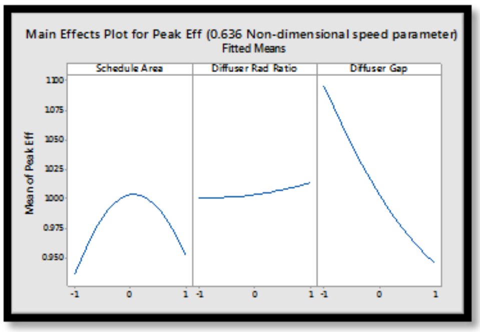

Figure 13: Main effects plot for Peak efficiency (0.636 non-dimensional speed parameter)

Interaction plot for Peak efficiency: Figure 14, shows Interaction Plots for 0.636 non-dimensional speed parameter from Minitab. Interactions can be seen between diffuser radius ratio / area schedule, diffuser gap/area schedule, area schedule/diffuser radius.

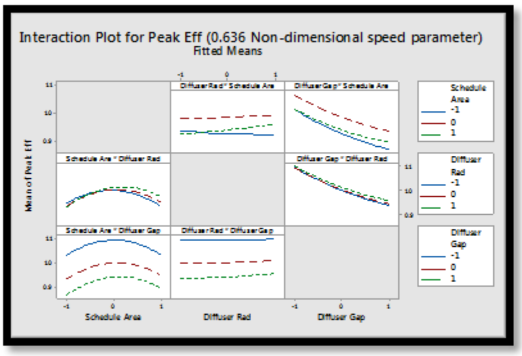

Figure 14: Interaction plot for peak efficiency (0.636 non-dimensional speed parameter)

The effect of speed parameter on the total to total isentropic efficiency: For speed line 0.636 non-dimensional speed parameter, most significant parameter affecting peak efficiency are area schedule and diffuser radius ratio. It can be also seen verified with figure 5.11, shown below as cavities 2,5,6,9,10,12,15 has lowest peak efficiencies whereas other cavities 1,3,4,7,8,11,13,14 has higher peak efficiencies compared to baseline.

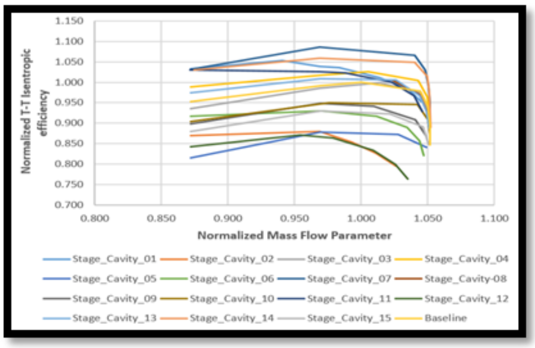

Figure 15: The graph of Normalized T-T Isentropic efficiency Vs Normalized Mass flow parameter for 0.636 non-dimensional speed parameter for all 15 stage cavities and baseline

Figure 16, shows cavities with lowest peak efficiency and highest peak efficiency compared to baseline. We can see that efficiency has marginally increased in cavity 14 at higher mass flow parameters comparing to baseline. For higher mass flow rate efficiency starts decreasing for cavity 12

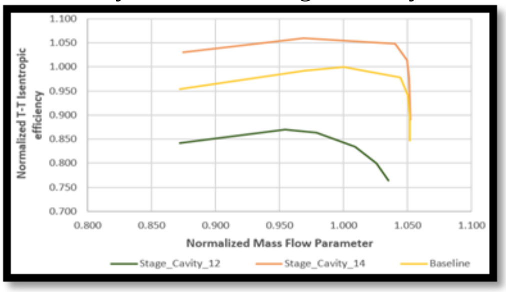

Figure 16: Normalized T-T Isentropic efficiency Vs Normalized Mass flow parameter (for 0.636 non-dimensional speed parameter)

VI CONCLUSIONS

Computational fluid dynamics analysis is carried out on 15 different cavities extracted by varying key design parameters (diffuser gap, diffuser radius ratio and area schedule).Response surface method using Minitab is employed to carry out the analysis in systematic manner and to understand effect of key design parameters on response. The study reveals the following

1. At lower speed lines diffuser gap has little or no effect on compressor stage peak efficiency whereas at higher speed lines, compressor efficiency drop considerably as diffuser gap level is increase from lower level (-1) to higher level (+1).
2. Diffuser radius ratio has slight or no effect on compressor stage peak efficiency.
3. With increase in area schedulefrom lower level (-1) to higher level (+1), compressor stage peak efficiency increases gradually attaining maximum value then decreases at all speed line.
4. The analysis for optimizing the diffuser gap, diffuser radius ratio and area schedule shows that maximum peak efficiency is obtained with cavity 14 having lower diffuser gap level (-1) and higher area schedule level (+1).
5. While the lowest peak efficiency is obtained with cavity 12 having higher diffuser gap level (+1) and lowest area schedule level (-1).

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