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Experimental optimization of the vanes geometry for a variable geometry turbocharger (VGT) using a Design of Experiment (DoE) approach

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ABSTRACT

In this paper, central composite design (CCD) based on Design of Experiment (DoE) is applied to obtain an optimal design of the vane geometry for a variable geometry turbine (VGT). The design is tested at four different pressure ratios (1.25, 1.5, 1.75 and 2.0) on a Garrett GT1541V turbocharger. Seventeen different cases for the inlet guide vanes are proposed. All cases, each having a unique combination of vane height, thickness, length and angle, has been produced via 3D printing. The goal of this study is to ascertain how vane geometry impacts turbine efficiency, so as to arrive at the ideal configuration for this specific turbine for the investigated range of operating conditions. As a main outcome, the results demonstrate that the applied vane angle has the strongest impact on the turbine efficiency, with smaller angles yielding the most favorable results. After CCD analysis, an optimized design for the vanes geometry with 76.31% efficiency (averagely in all pressures) is proposed. As a final step, all cases are analyzed from a free space parameter (FSP) perspective, with the theoretically optimal design (e.g., FSP < 5) corresponding nicely to the best experimental results.

1. Introduction

The first concept of a turbocharger was proposed by Dr. Alferd J. Buchi in 1915, who developed it for a diesel engine [1]. In a turbocharger, a turbine propelled by exhaust gas is coupled via an axle to a compressor, which in turn boosts engine power by compressing inlet air above its default atmospheric pressure. One of the main challenges for turbochargers is a phenomenon known as turbo lag, a delay in boost pressure owing to gaseous and rotational inertia in the system. Turbo lag can be reduced significantly by using two stages turbochargers and/or variable geometry turbines (VGT) [2,3].

This study will focus on improving the VGT efficiency. There have been many studies on how to improve efficiency by means of new designs, particularly of the inlet guide vane configuration. Eichhorn et al. [4,5] evaluated the efficiency of a variable geometry turbine by means of free space parameter (FSP) theory to improve the efficiency of the turbine. The authors report a 3–28% improvement in efficiency over a range of pressure ratios.

Fu et al. evaluated two novel turbocharger concepts, namely steam turbocharging [6] and steam-assisted turbo charging [7], which make use of a Rankine steam cycle system that converts thermal energy in the exhaust via steam into rotational energy in a turbine. Their results suggest that engine power and thermal efficiency can be improved by 7.2% and 2%, respectively. Moreover, in a third study [8] the authors compared two kinds of novel pressure boosting designs, using again steam turbo charging and steam-assisted turbocharging. Results indicated that with increasing engine speed, the exhaust gas energy recovery efficiency of steam turbocharging system decreases to 6.5%.

Kesgin [9] investigated the effect of turbocharging on different types of gas engines, which were used in combined heat and power plants. The author studied the effect of exhaust manifold and turbine exit diameter, as well as location of the turbocharger on efficiency using a zero dimensional computational model. Samoilenko and Cho [10] investigated the influence of turbine adjustment in a turbocharger with a vaneless turbine volute on diesel combustion efficiency and emission characteristics. The authors introduced a new configuration based on the cross-sectional variation of the turbine volute acceleration section by means of a specially shaped

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element located in the inlet part of the volute. Said element could move either in the direction of incoming gas flow or in the opposite direction to change the inlet cross-sectional area. As a result, this configuration lead to reductions in CO of 10.1%, PM of 19.23%, and specific fuel consumption (SFC) of 0.6%.

Another experimental VGT study, by Wahlstrom and Eriksson [11], looks at a two-stage configuration. The performance of which is later analytically investigated by Galindo et al. [12]. A review on various turbocharger concepts configuration by Aghaali and Ångström [13] discusses the best fit for a given set of operating conditions.

Although some optimization studies have been performed for compressor [14] and pump-turbine [15] vanes, no optimization study on the VGT inlet guide vane geometry could be found. Accordingly, in this experimental study the main objective is to improve the efficiency of VGT turbines by means of vane configuration optimization using central composite design (CCD). Hereby, the CCD method will be compared to a theoretical model based on free space parameter (FSP) theory [5].

2. Design of Experiments (DoE) and central composite design (CCD)

DoE is a collection of mathematical and statistical techniques to reduce the number of experiments in order to find the effect of parameters affecting a response in a process, thereby aiming for a reduction in both costs and time [16–20]. Generally, the structure of the relationship between the response and the independent variables is unknown. The first step in DoE is to find a suitable approximation close to the true relationship. The most common forms are low-order polynomials (first or second-order). A second order model can significantly improve the optimization process when a first order model is not usable due to interaction between variables and surface curvatures. A general second-order model is defined as [17]:

$$y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x_i^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij} x_i x_j \big|_{i<j} \tag{1}$$

where x_i and x_j are the design variables, a the tuning parameter and n the number of parameters (in this case four). A Box–Wilson Central Composite Design, commonly referred to as a "central composite design" or CCD is one of options in DoE which helps the user in defining the factor levels.

CCD contains an imbedded factorial or fractional factorial design with center points that are augmented with a group of 'star points' that allow an estimation of the curvature. If the distance from the center of the design space to a factorial point is ±1 unit for each factor, the distance from the center of the design space to a star point is ±α for |α| > 1. The precise value of α depends on certain properties, the design and the number of factors involved [16–20].

With CCD, optimization is based on a parameter called 'desirability'. Desirability is an objective function ranging from 0.0 outside of the limits to 1.0 at the goal. The numerical optimization finds a point that maximizes the desirability function. The characteristics of the goal may be altered by adjusting the weight or importance. For several responses and factors, all goals get combined into one desirability function. In this paper, one response is defined as turbine efficiency. The goal of optimization is to find a set of conditions that meet all the goals, not to get a desirability value of 1.0. Desirability reflects the preferred ranges for each response (d_i). The simultaneous objective function is a geometric mean of all transformed responses:

$$D = (d_1 \times d_2 \times \ldots \times d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}} \tag{2}$$

where n is the number of responses in the measure (in this case, $n = 1$). If any of the responses or factors falls outside their desirability range, the overall function becomes zero. For simultaneous optimization, each response must have a low and high value assigned to each goal. On the CCD worksheet, five choices are possible in the "Goal" field for responses: "none", "maximum", "minimum", "target", or "in range". In this study, the goal parameter used is "maximum" (for turbine efficiency) as follows:

$$\begin{aligned} &d_i = 0, && Y_i \leqslant \text{Low}_i \\ &d_i = \left[\frac{Y_i - \text{Low}_i}{\text{High}_i - \text{Low}_i}\right]^{wt_i}, && \text{Low}_i < Y_i < \text{High}_i \\ &d_i = 1, && Y_i \geqslant \text{High}_i \end{aligned} \tag{3}$$

where Y_i is the ith response value and wt is the weight of that response. Weight adds emphasis to the goal. A weight greater than 1 (maximum weight is 10), emphasizes the goal and less than 1 (minimum weight is 0.1), deemphasizes the goal. In this paper, just one response is defined, so the weight will have a negligible effect on the final results.

3. Experimental procedure

As described earlier, the aim of this study is to find an optimum design for different variables concerning VGT inlet guide vanes.

Table 1
Specifications of the GT1541V turbocharger [5].

Number of stator vanes (N_v)	10
Number of rotor vanes (N_r)	9
Rotor inlet radius (R_4) (mm)	19.3
Rotor outlet radius (R_5) (mm)	14.3
Rotor hub radius (R_{hub}) (mm)	5.85

Table 2
Maximum and minimum values for the considered parameters.

Values	Parameter 1 Length (mm)	Parameter 2 A	Parameter 3 Maximum thickness (mm)	Parameter 4 Height (mm)
Minimum	15.66	65	1.95	3.15
Maximum	19.14	85	3.25	5.25

Table 3
Different cases proposed by DoE.

Case number	L (mm)	A	T (mm)	H (mm)
1	17.4	75	2.6	3.15
2	19.14	65	1.95	5.25
3	19.14	75	2.6	4.2
4	17.4	75	3.25	4.2
5	15.66	85	1.95	5.25
6	17.4	75	2.6	4.2
7	15.66	65	3.25	3.15
8	15.66	65	1.95	3.15
9	17.4	65	2.6	4.2
10	15.66	75	2.6	4.2
11	17.4	85	2.6	4.2
12	19.14	85	3.25	3.15
13	15.66	85	3.25	5.25
14	19.14	85	1.95	3.15
15	19.14	65	3.25	5.25
16	17.4	75	2.6	5.25
17	17.4	75	1.95	4.2